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AN INVESTIGATION OF THE POWER SPECTRUM
OF UNDERWATER EXPLOSIONS OF GASEOUS
HYDROGEN AND OXYGEN

Jack R. Harris, et al

Naval Postgraduate School
Monterey, California

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by

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and

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
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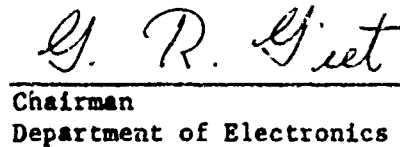the thesis requirements for the degree of

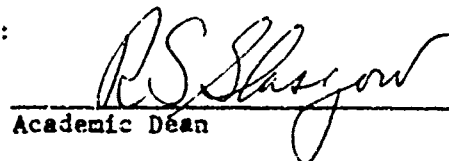MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

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Faculty Adviser

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Faculty Adviser

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Chairman
Department of Electronics

Approved:

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Academic Dean

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ABSTRACT

This thesis was inspired by the need for investigation of new
methods of producing underwater sonic energy for possible use in signal-
ing and detection. Electrolysis of sea water into hydrogen and oxygen
and the detonation of this mixture underwater was chosen as the trans-
mitting source since it provides a simple and non-depth limited system
usable from shipboard, submarine and airborne platforms. The fundamental
source of energy to the transducer is high current, low voltage DC elec-
trical power in magnitudes now available from the three possible plat-
forms. A working unit was made and the pressure vs. time and pressure
vs. frequency spectrums analyzed for selected parameter changes of depth,
gas volume and mixture ratios.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction

This thesis is primarily a basic research project concerned with the time and frequency domains of an underwater explosion resulting from the recombination of hydrogen and oxygen.

Motivation was provided by the needs of the Navy for more effective underwater signaling and active echo ranging devices. The field of study chosen was governed by the need for a system that would allow large quantities of peak power, such as from explosives, but still be of a non-destructive nature and repetitive so the logistic problems would not hinder the most effective use of the device on ASW missions.

The system developed uses the recombination of gaseous hydrogen and oxygen to produce the sound energy. Three basic methods of obtaining the gas mixture were considered, namely, the use of bottled gas, the use of hydrogen obtained from electrolysis and mixed with air or oxygen, and the use of electrolysis alone for the gaseous products. Both the first and second methods are considerably simpler to work with from the controlled measurement standpoint, but the third method was chosen since it alone offered a possibility of deep water operation (hundreds of feet) without creating the additional problems of using armored flexible tubing and sufficient pressure to operate at great depths. These problems in addition to that of handling great lengths of armored cable from a slow-moving airborne platform (airships or helicopters) convinced the investigators that the method of utilizing electrolysis only was the one to initially pursue.

Considerable difficulty was originally experienced in obtaining oxygen from sea water, as is described in Section 2, but a working

1

system was finally made and operated to depths of 375 feet. This depth limit was a function of the length of cable only and not of the transducer.

When the working transducer had been developed, the problems associated with the analysis of the time and frequency spectrums were examined for the three parameters to be studied; depth, mixture and quantity of gas. After being able to produce repetitive explosions at will under constant input conditions, the effect of the three parameters were measured within the limitations of the equipment available at the time.

A major measurement limitation was the effect of surface reflections on the waveform as received at the hydrophone. The hydrophone used was limited in the depths at which it could be placed due to pressure and cable length, making it impossible to avoid the surface reflection problem in some cases. Even so, a series of over 200 explosions at depths from 15 feet to 375 feet with bottom ranging (echo) information to 3000 feet were measured successfully. The analysis of this information allowed qualitative conclusions to be drawn with regard to the spectrum changes accompanying the controlled parameter changes. The results obtained were very satisfactory and indicate that further work in the field is warranted along with investigation of many of the associated areas of the study related to chemistry and physics.

To augment our measurements special use was made of the Hughes Memoscope for time spectrum measurements and a specially designed frequency spectrum analyzer for low audio frequency spectrum measurements. Due to the severe environment (the ocean) and the range of audio

frequency investigated (30 to 600 cps.) care was taken to insure the validity of our techniques. Factors considered were the linearity of the hydrophone to input level and the tape recorder power and frequency linearity for different input levels. These checks and procedures, along with the circuit and development of the frequency analyzer, and related measuring devices and techniques, are described in the appendices

It would be appropriate here to mention and thank the many people and organizations who made their time and equipment available for use in this study. We wish to thank the U. S. Naval Underwater Sound Laboratory at Orlando, Florida for the loan of a J2 transducer and M115B Hydrophone; the Naval Electronics Laboratory at San Diego, California, for advice and loan of equipment related for the frequency analysis; and to the Bendix Pacific Corporation of North Hollywood, California, who supplied us with services during our ten week industrial tour. It was during this tour that the actual sea tests and measurements were conducted using the Bendix boat "Sonar Queen".

Our grateful appreciation is also extended to the following persons associated with Bendix Pacific; Mr. Dave Sherwood, Chief Engineer of ASW, for the use of his staff and facilities, and Mr. Vincent Stewart and Mr. Benjamin Manierre who worked enthusiastically side by side with us on the equipment and measurements regardless of the hours.

Special thanks are given to Chief Boswell, USN, of the U. S. Naval Postgraduate School who personally handled the construction and building of much of the equipment and offered very welcome advice regarding its design.

Finally, our sincere gratitude to Captain Louis Spear, USN, and

3

Professor Carl Menneken of the U. S. Naval Postgraduate School who believed in the project and through whose efforts funds were obtained to support the study and assure its success.

2. The Transducer Design

The decision to use the mechanism of electrolysis to produce the gaseous hydrogen and oxygen was followed with a series of experiments to show the feasibility of the gaseous production. Knowing that the salinity of ocean water is fairly constant, i.e., 33 to 37 parts per thousand,[6] a sample of local ocean water was obtained and processed by electrolysis. Reference to standard chemistry handbooks (bibliography numbers 1, 2 and 3) on electrolysis and ionization of liquids indicated that the electrolysis process would be of a complex nature in ocean water, the results being dependent upon the current density, temperature and chlorinity of the solution. Appendix A describes the experimental setup along with typical values of H_2 vs. O_2 (plus some Cl_2) production.

The results of these tests implied that a hydrogen to oxygen ratio of about 20 to 1 could be expected under cold water conditions (about 50° F.) and low current densities (less than $\frac{1}{2}$ ampere per square inch). This deviation from the normal 2 to 1 ratio of H_2 and O_2 composing water is apparently due to the complex ion relationship present in sea water during electrolysis, and to the fact that the oxygen is released only to recombine back into solution. The ease with which the chlorine is released is also an important factor.

It was realized that production of the gases as described resulted in operating efficiencies of about 10% even before the explosion took place, but it still represented a satisfactory method of allowing a qualitative investigation of the spectrums produced on explosion of the gases.

5

After observing that H_2 and O_2 production was possible in sea water, an investigation was carried out involving the use of other metals instead of platinum for the electrodes. Metals such as gold, silver, cadmium, carbon, aluminum, tin, copper, lead and nickel were tried. Any of these metals operated with about equal success as the hydrogen producing plate, but only the noble metals proved satisfactory for oxygen production. Apparently the other materials oxidized instead of releasing the oxygen. Gold produced about the same quantity of free oxygen as platinum but rapidly dissolved in the chlorine laden water. It was therefore decided that only platinum could satisfactorily serve as the anode, whereas any of the more common metals could be used to form the cathode for this project.

Another factor for consideration was the method to be used to proportion the hydrogen and oxygen within a range of ratios where an explosion could take place. It was determined that low hydrogen to oxygen ratios would explode readily, but when an excessive amount of hydrogen was present, relative to a perfect 2 to 1 ratio, no combustion could be initiated, either by glow plug spark discharge or flame. In addition to this, since the mixture was one of the parameters to be varied, the ability to easily adjust the H_2 to O_2 ratio was desirable. This problem was solved by use of a losser method to rid the combustion chamber of excessive hydrogen. Use of an electrolytic tank indicated that, if a metallic container, acting as the cathode, were lined internally with a plastic insulation and open at one end with the oxygen electrode (anode) placed inside, sufficient gradient lines would exist to allow current passage of reasonable magnitude. The outcome of

this would be an electrolysis process in which the oxygen bubbles would rise and be trapped internally while the hydrogen bubbles would rise freely to the surface, being formed on the outside of the container. With this method of separating the gases, it was only necessary to have a small part of the cathode exposed inside the insulating container, thereby allowing some hydrogen bubbles to collect and become mixed with the oxygen. The proximity and area of the interior hydrogen electrode relative to the oxygen producing plate and the outside cathode would then determine the H_2/O_2 ratio.

The experimental transducer constructed for this project had a machine screw threaded through the metallic jacket and insulator, extending into the interior of the container to serve as the hydrogen producing electrode for the explosive mixture. This screw could be easily rotated in or out to adjust the mixture.

The method of igniting the contained gas mixture was one that adapted itself to the high current low voltage power available, namely, a red hot wire or glow plug. Originally spark ignition was used with success, but severe difficulties exist in supplying the required high voltage to large depths in a sea water environment due to high leakage losses and shorting at the plug's electrodes. A vibrator or transformer could be placed at the transducer allowing a low voltage to be transmitted down the cable, but this would place a crush depth limitation upon the device due to sealing of the electrical device against salt water penetration and still not solve the shorting problem at the electrodes.

The ignitor itself was a nichrome wire heated to a red hot

temperature. The particular wire used demanded about 20 volts at 15 amperes to heat it to ignition temperature. This wire, wound into a ½ inch diameter coil about one inch long, was built into a plastic cap which screwed onto the top of a large polyethylene acid bottle. This bottle, with the bottom cut out, served as the insulator inside a ½ inch wall steel cylinder which formed the hydrogen producing electrode. A photograph of the basic transducer and a later modification of the same follows (plate 1). Appendix B contains the construction details of this transducer. The modified unit had a 30 inch cylindrical extension fastened to the opened end. This was necessary to allow for vertical movement of the device caused by wave motion action on the boat. Without this, gas released on the outside of the container intermixed and diluted the trapped gas inside, destroying the accuracy of the mixture tests. This intermixing was caused by turbulence around the open bottom of the transducer drawing in the external gas as the device moved up and down in the water. Windows were cut in the sides of the extension near the end of the main unit and covered with fine cloth gauze. This gauze prevented the hydrogen bubbles from entering the container while still allowing the electric gradient lines to exist so that a reasonable amount of current could flow without demanding excessively high voltage.

The amount of gas formed, therefore the potential energy of the transducer, is proportional to the current x time product. To control the current to the transducer, a power distribution panel was constructed which allowed accurate voltage and current regulation. Appendix C contains the electrical diagram and photographs of this
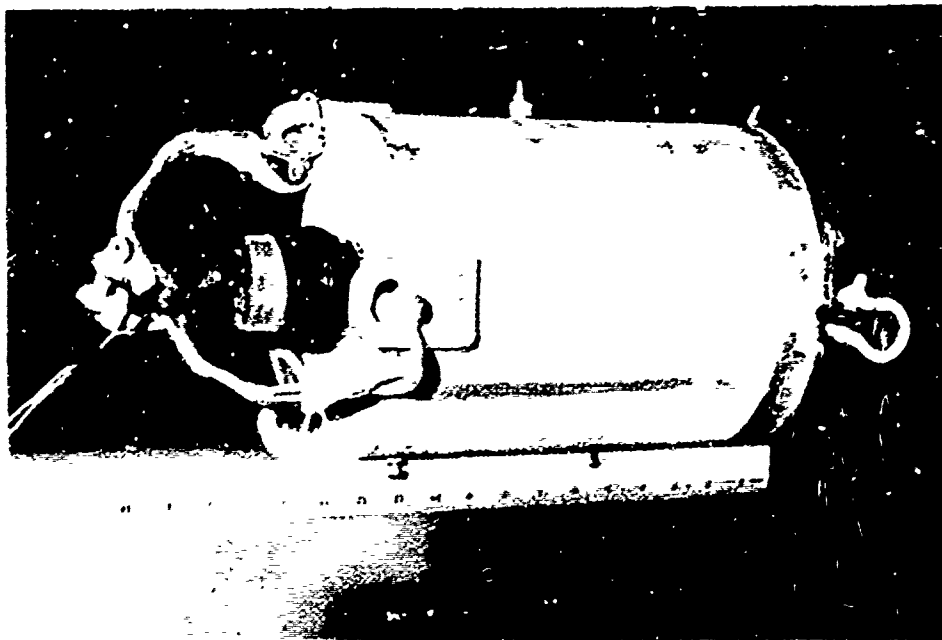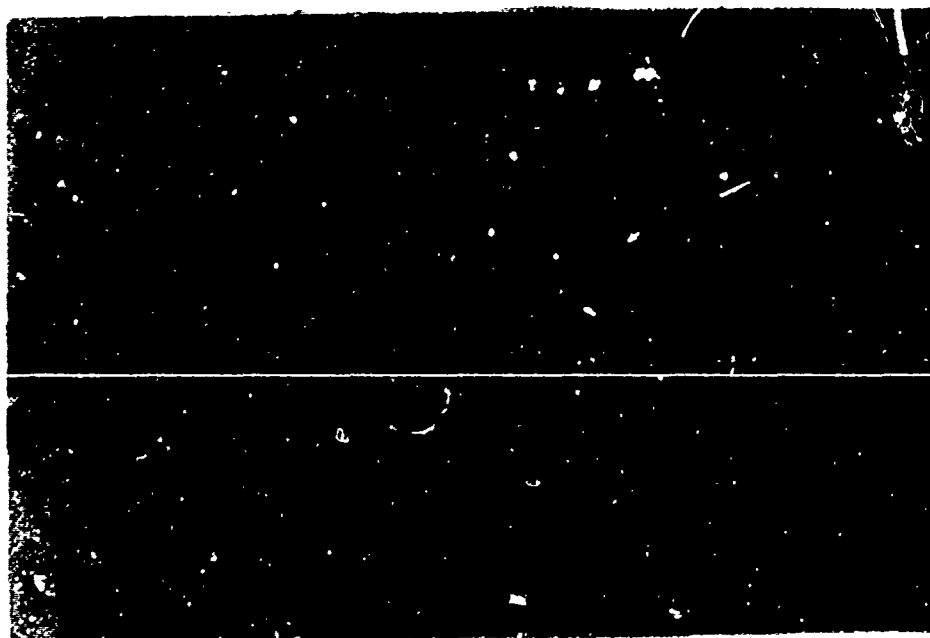
control panel. The source of power was a set of 6 volt lead-acid batteries (automotive capacity) with from 6 to 12 in series, depending upon the voltage called for in the tests.

The cabling to the transducer consisted of four plastic insulated #6 gauge wires for the electric power to the ignitor and gas forming electrodes. These were augmented with a hoisting line to support the entire unit, and a tilting line to allow dumping any unburned gases out of the transducer after each explosion. This six piece cable was over 400 feet long to allow operating the transducer to that depth. The input resistance of the gas-forming plates of the transducer in sea water was about $2\frac{1}{2}$ ohms measured through the cabling, with about $\frac{1}{2}$ ohm due to the resistance of the wire itself. Current rates of 13 and 25 amps were used for the controlled tests. These were well within the current densities which were experimented with in the laboratory.

Photographs (plate 2) of the cable reels and control panel situated on the bow of the 63-foot boat "Sonar Queen", which served as the measurement platform, are included on the following pages.

HOISTING AND ELECTRICAL CABLE AND REELS
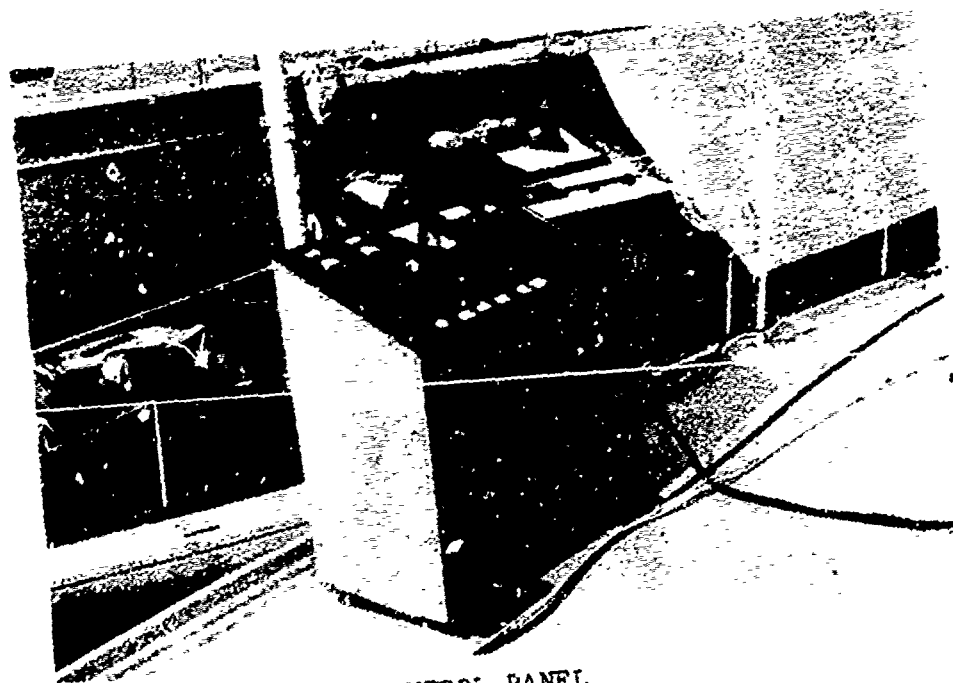
ELECTRICAL CONTROL PANEL

PLATE 2

3.   Measurements and Results

Tests involving parameter changes of depth, mixture and charging
time were carried out off San Pedro, California, aboard a 63-foot
boat in water depths of from 26 to 3000 feet. Over 200 explosions were
made, with the pertinent runs analyzed in the frequency and time domain.
Water conditions were checked periodically for temperature and density,
and the salinity was calculated. A nearly consistent salinity of
34 parts per thousand was found to exist which agreed with the expected
salinity for these latitudes.

Due to the amplitudes of the pressure waves and low frequencies
encountered, several qualifying tests had to be made on the hydrophone,
tape recorder and frequency analyzer. Appendix D discusses the analysis
of the linearity of the M115-B hydrophone and its preamplifier with
respect to large amplitude signals; Appendix E covers the particular
procedures used to frequency calibrate the M115-B hydrophone down to
30 cps; Appendix F contains graphs of the frequency response of the
tape recorder for different input levels and discusses how the frequency
range was extended; and Appendix G is the circuit of the frequency ana-
lyzer along with a description of its operation and charts verifying
its frequency and amplitude dependency.

The standard technique used to record the underwater explosion
produced by the transducer was to have the Massa Lab M115-B hydrophone
connected to its preamplifier, the output of which was fed to an
Ampex 600 tape recorder which recorded the explosion on high quality
magnetic tape. This taped explosion was then transmitted to a Hughes
Memoscope (a storage tube oscilloscope) where it was possible at sea to

immediately analyze the time-amplitude domain of the explosion. This in situ observation of the results gave immediate information of any trends produced by the various parameter changes. Polaroid photographs were then made of these time domain pictures on the scope. As a further check to show that the tape recorder was not modifying the explosion spectrum, the input of the Memoscope was connected directly to the output of the hydrophone preamplifier, by-passing the tape recorder, in order to obtain a direct trace of the explosion pressure wave. At the same time, the explosion was recorded on tape. These two waveforms were then compared, using the storage ability of the Memoscope. At no time was there any significant difference, thereby upholding the validity of the methods employed.

For the runs of interest, the taped explosions were separated and formed into closed loops of tape, thereby allowing the signal to be played back continuously. This repeating signal was then fed to the frequency analyzer which produced the frequency vs. pressure amplitude trace on the Memoscope for photographing. In particular, only the 0-600 cps. spectrum was photographed, no major peaking of amplitudes of the higher frequencies being observed for any of the explosions. A discussion follows for the important factors measured and considered by this investigation, along with photographs of the results.

hepetition: Before any measurements could be made of the effect of parameter changes, it was necessary to verify the ability o repeat an explosion signature with the same parameter settings. By insuring a fixed distance between the transducer and the hydrophone, a constant current and a constant charging time, a series of explosions were made

11

and photographed. On the following page (plate 3) photos 1-4 are the time/pressure domain of four different explosions under these similar conditions. These particular explosions are representative of a nearly perfect gas mixture (little unburned gases left). Photographs 5-8 are of another series of runs using a hydrogen-rich mixture under similarly controlled conditions. Here again a good comparison exists, showing the repetitiveness of the installation even though the sea state was changing considerably during the tests. For all eight photographs, the time scale shown is 20 milliseconds per division. It was considered that a high degree of correlation existed in the time/pressure domain, and therefore any changes in the spectrum would represent the influence of the controlled parameter changes.

Reflectivity: The presence at the hydrophone of both a reflected and incident wave from the transducer complicated the analysis of some of the results. For this installation, the M115-B hydrophone could not be lowered more than 30 feet below the surface of the water due to limited cable length. The theoretical analysis was complicated by virtue of the fact that for the deep water tests both the bottom of the boat (wood and metal) and the surface of the water served as reflecting mediums with different phase-reversing characteristics. A series of tests were made to show the effect of these reflections upon the wave forms. Plate 4 of the illustrations shows two such tests. Photograph 9 is a picture of the pressure/time waveform of an explosion under conditions of spacing where the surface-reflected wave would be a maximum of 1/20 of the amplitude of the incident wave with a phase delay of approximately 5 milliseconds; or for all intents and purposes,

12.
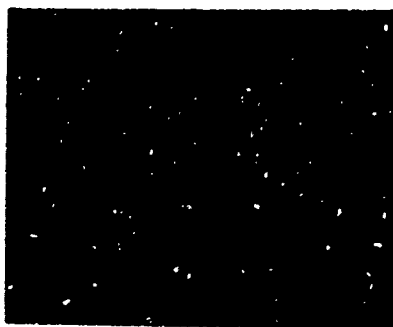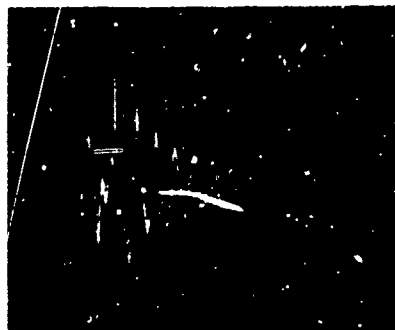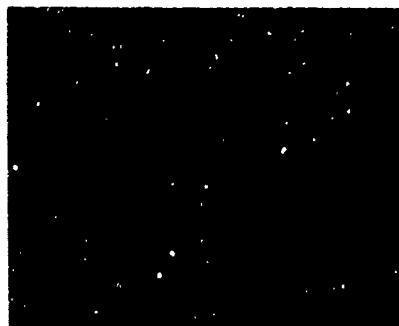
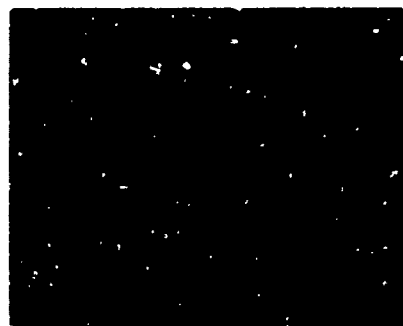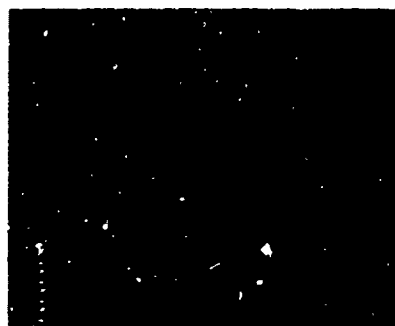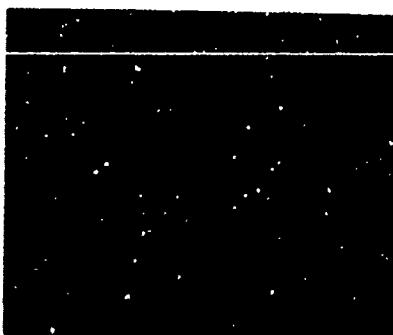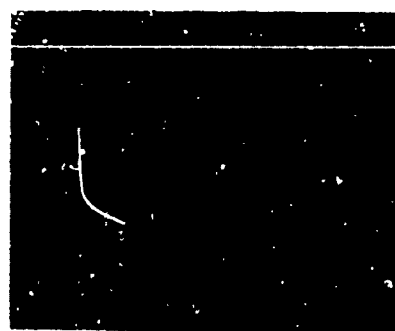(1) 20 ms/div

(2) 20 ms/div

(3) 20 ms/div

(4) 20 ms/div

(5) 20 ms/div

(6) 20 ms/div

(7) 20 ms/div

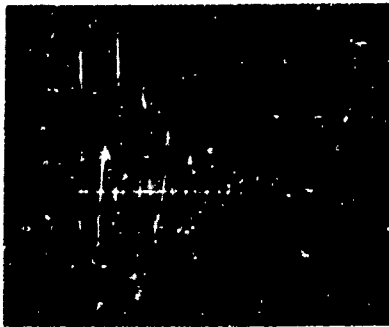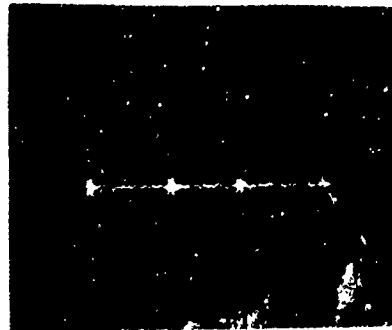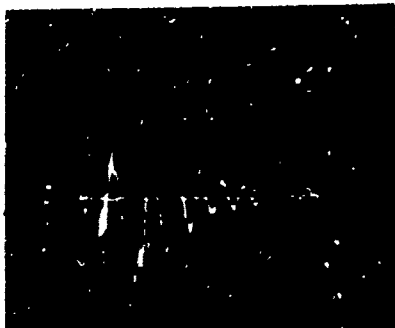(8) 20 ms/div
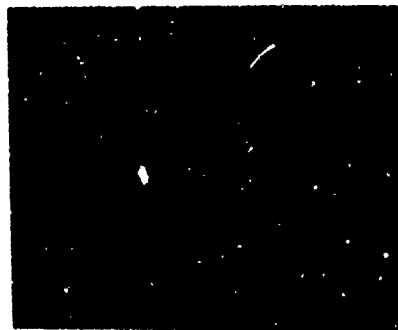
PLATE 3

12-4

(9)   20 ms/div
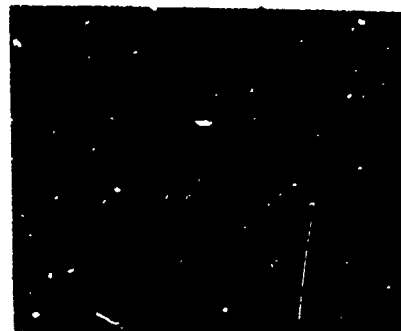

(13) 100 ms/div

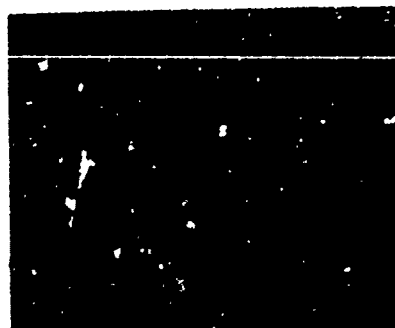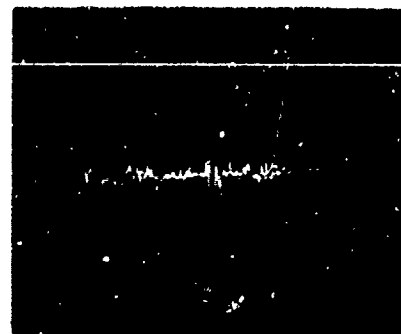(10)   20 ms/div

(14)   2 ms/div

(11)   20 ms/div

(15) 2 ms/div

(12)   20 ms/div

(16)   2 ms/div

PLATE 4

12-b

it is a photograph of the incident wave only. Photograph 10 is of a similar explosion with the hydrophone so placed that the reflected wave would be $\frac{1}{4}$ *less than* of the incident wave amplitude. Both photographs have been normalized for ease in direct comparison. Photograph 10 is also a true representation of the explosion within repetitiveness correlation, and is typical of the spacing used for the runs which were made for variable mixtures.

Another series of runs was made to check again the effects of reflectivity along with the investigation of the vertical and horizontal radiation pattern of the transducer. Photograph 11 is of an explosion with the transducer 12 feet from the surface and the hydrophone 5 feet directly above the transducer. Photograph 12 shows a similar explosion with the hydrophone at the same depth as the transducer but 27 feet horizontally from it. Again the amplitudes of the photographs have been normalized to allow accurate comparison. There is good similarity between the two waveforms except for the relative heights of the sharp shock wave spikes. However, these varied less than 3 db from each other.

Unfortunately, the evidence is inconclusive as to the actual importance of the reflected wave effect on the waveforms. In both of the tests the factor which makes it difficult to decide on the reflection problem is the long duration of the incident signal relative to the reflection delay time. However, when deep transducer tests were run, the duration of the signal was short enough to check independently for the reflected signal. One run which allowed this to be done was a 375-foot transducer depth explosion which took place off Catalina Island.

Photograph 13 shows the time/pressure graph of the initial explosion followed by two echoes, corresponding to the bottom and an underwater ledge between the transducer and the Island. As shown in photograph 14, which is a time expansion of the initial explosion, the pulse actually consists of two separate pulse groups with a phase reversal and a delay of about 12 milliseconds. The particular setup for this run could have produced a 10 millisecond phase reversed signal from the surface of the water, but to complicate matters, it is believed possible, under these high water pressures, to have a double explosion take place which could also have this time/pressure signature. Several other explosions were recorded which produced similar delay features in the initial waveform that could not be explained by any reflections. Another complicating observation which tended to support the existence of a double explosion was the detailed blow-up of the third pulse which corresponds to the shelf reflection (photograph 15 . This shelf was so positioned as to have any surface reflected signal about 5 milliseconds later than the incident shelf echo. An analysis of this photograph shows a slight increase in signal amplitude about 5 milliseconds behind both the main pulse and the secondary pulse. If this slight increase is taken to be a weak surface reflection, then the secondary pulse of this group can be assumed to be actually the incident shelf echo of a second explosion. Unfortunately, there is also a small pulse between the main and secondary pulse of the bottom echo group (photograph 16). The time spacing does not correspond to a surface reflection based upon careful calculations of the trigonometric problem drawn to scale. The sharp spike is believed to be due to a transient caused by some electrical

14

equipment on the boat. The refrigerator was automatic and sometimes

started up during the runs, although no other cases were observed

where it interferred with the test results.

In general, the reflection problem was not resolved as far as

this investigation was concerned (deep water explosions), but this

does not influence the qualitative discussion with respect to changes

of the transducer depth. The mixture and charging rate tests have

reflections as a second order effect, due mainly to the longer path

lengths of the reflected wave compared to the incident wave. These

latter tests were run with the transducer at shallower depths.

Mixture: The first series of parameters investigated, both quali-

tatively and quantitatively, was the time and frequency domain of the

gaseous explosion for the same current density and time, but with

different ratios of hydrogen and oxygen. As discussed in section 2,

the mixture was changed by the amount of hydrogen which was allowed

to form within the combustion chamber. With constant current, the

same amount of oxygen was being formed with different controlled

amounts of hydrogen mixed with it.

The determination as to whether the mixture was oxygen or hydrogen

rich was accomplished by simply analyzing the combustive nature of the

gas remaining in the transducer after an explosion. If the gas could

be ignited after the addition of a controlled amount of air, then

excess hydrogen remained and the original mixture was termed hydrogen

rich. Once this was determined, the particular characteristics of the

explosion plot on the scope could be attributed to the type of mixture

which was present. Photograph 17 of plate 5 represents a slightly

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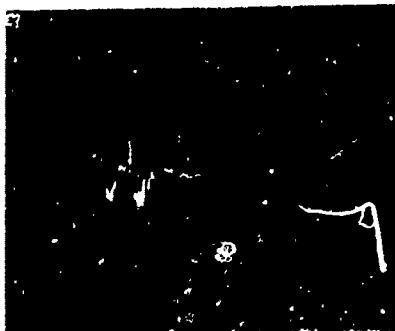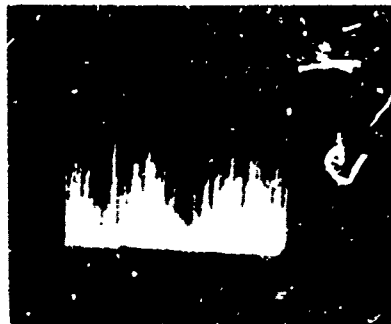
(17) 20 ms/div

(21) 0 to 600 cps
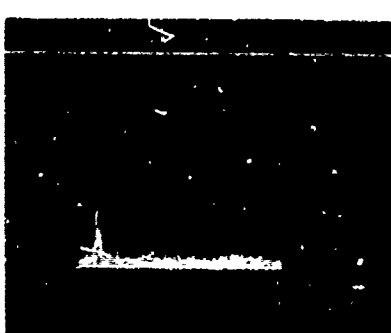
(18) 20 ms/div

(22) 0 to 600 cps

(19) 20 ms/div

(23) 0 to 600 cps

(20) 20 ms/div

(24) 0 to 600 cps

PLATE 5

15-a

oxygen rich mixture, typified by a large output of energy with short pulse length (about 40 ms). Of interest is the high frequency signal (about 250 cps.) superimposed on the pulse, apparently a function of the vibration of the small amount of gas remaining in the transducer dome. Photograph 21 is the qualitative frequency/pressure spectrum of this same pulse, showing a fairly broad band output as would be expected from a sharp pulse type signal. Photograph 18 is of a hydrogen rich mixture upon exploding, showing the formation of a longer pulse with shorter peak amplitude. Here one can observe the formation of a semi-discrete frequency component which can be attributed to the vibration of a larger bubble of gas remaining. A discussion of this bubble vibration is contained in reference 4 of the bibliography. Photograph 19 shows an explosion under the same conditions as 18, only more hydrogen rich. The energy output of the oscillating bubble is very evident here. Photographs 22 and 23 show the frequency spectrum runs for this explosion, showing a definite pressure increase at about 45 cps. The frequency analysis was done twice to show that this particular analyzer, by the nature of its construction, cannot be expected to completely correlate for each run, as evidenced by the slight dissimilarities between photographs 22 and 23. It can be seen, however, that major qualitative conclusions can be drawn as to definite power output peaks and their frequency.

Photograph 20 is of the waveform of a very hydrogen rich mixture, showing no shock type pulse at all, only the bubble vibration. Photograph 24 is the frequency analysis for this same run and is striking in that it shows the output to be of nearly a single frequency with

16

regard to energy concentration. Run 20 was done under slightly different conditions than 17, 18 or 19, but still is typical of the nature of a very rich hydrogen mixture.

All the above mentioned runs were made with the hydrophone 5 feet vertically from the transducer with reflection effects not considered. Transducer depth was about 15 feet.

In conclusion, the spectrum output is greatly affected by the hydrogen/oxygen mixture, with approximately the same energy possible either in the form of a short pulse, broad frequency signal or a long pulse, single frequency signal. Pulse lengths up to 700 milliseconds were observed. These tests were run with current densities of about $\frac{1}{2}$ ampere/square inch for the oxygen plate. An investigation of the frequency spectrum above 600 cps. (up to 4400 cps.) revealed no major energy peaks.

Charging Rates: The next series of test runs involved the control of charging time and current. Plate 6, photograph 25 is the time domain spectrum of a 13 ampere, 15 minute charge exploding, while photograph 26 is one where 13 amperes were used for 30 minutes. An investigation of the two shows that over twice as much energy was released from the second charge (the amplitudes proportional to the square root of the power) and that the bubble period indicates a natural relaxation frequency of 48 cps. for the 15 minute charge and 38 cps. for the 30 minute charge. These factors show a good correlation with theory and will be compared with simple bubble oscillati formula later.

Photograph 27 is for a 15 minute charge at 26 amperes, representing

CHARGING RATE TESTS

(25)   20 ms/div

(26)   20 ms/div

(27)   20 ms/div

(28)   20 ms/div

PLATE 6

17-a

the same input power as photograph 26. A near perfect correlation exists between these two shots except that the higher current shot (photograph 27) shows more energy output and a slightly lower bubble frequency of 35 cps.

Photograph 28, representing a 7.5 minute charge at 26 amperes, the same input power as photograph 25, again shows excellent correlation for the two runs except for a slightly higher power output and lower frequency of 45 cps.

As discussed in reference 4, an expression of the initial frequency of oscillation of a vibrating spherical bubble is given by

frequency $= K \times \dfrac{P^{5/6}}{E^{1/3}}$ where K is a constant of proportionality, P is the pressure under which the bubble is statically influenced, and E is the energy involved in the bubble. This energy is approximately proportional to the product of input current and charging time, and as such, allows comparison of the individual runs. This formula pertains to a bubble vibration caused by a high explosive, where the actual explosive process is relatively independent of external pressure. In the case of this investigation where gas products are used as the explosive mixture, and the explosive process is dependent on the pressure exerted on the gases, this formula is more accurately represented by $F = \dfrac{K \times F(P)}{E^{1/3}}$ where F(P) denotes a complex function of pressure.

Comparing the runs represented by photographs 25 and 26 discloses a ratio of bubble frequencies of 1.26 which is verified theoretically by the above relationship. This same ratio is also verified for

photographs 27 and 28. In fact, K can be found for these runs by assigning appropriate values for E and P. Using E in amperes per minutes and P in atmospheres gives a value of 4960 for K. This K is only valid for this particular hydrogen/oxygen ratio and depth for it appears that the amount of energy released in shock form and the amount left for bubble vibration is a function of the H_2/O_2 ratio, as indicated by the mixture runs.

It is interesting to note the correlation that exists between the results of Appendix A and this set of runs where, at higher current densities, a greater energy output was obtained for the same input power. Appendix A states that a greater percentage of oxygen and chlorine gas is evolved at higher current densities. This higher percentage of gas output produces a larger release of energy upon recombination with a corresponding effect on frequency and pressure amplitude.

It was concluded that an investigation of higher current densities is in order, since this increases the percentage of oxygen and chlorine evolved, and thereby becomes the limiting factor on energy output. The dependency of the bubble frequency on input power allows some control of the frequency of the unit as well as the energy output, important factors when considering the device for possible use in signaling and detection.

Changes with Depth: The last major parameter change that was studied was the effect of transducer depth on the time domain spectrum. Runs were made with equal input current and depths ranging from slightly below the surface to 375 feet. As mentioned in the discussion on reflection, these runs do not necessarily present the exact spectrum,

especially the deep water explosions where the total path lengths between the incident and reflected waves are nearly identical. This does not invalidate the analysis of qualitative changes due to depth, however. The measurement technique used involved the electrolysis process taking place at the depth at which the device was ignited, thereby allowing another variable to enter in, i.e., the effect of gas evolution under high pressure. It was not possible to investigate this phenomenon separately due to shortage of time, but it repr. ents an area that should definitely be studied in any future work in this field.

Plate 7, photographs 29 through 32, inclusive, are of the explosions made with identical input current and mixture settings, but for depths of 25, 100, 275 and 375 feet, respectively. Photograph 33 is the run at 375 feet with an expanded time scale, while photograph 34 is the frequency spectrum of this same run. Of interest is the fact that the pulse width is continuously lowering with depth, while the peak pressure output increases with depth. This is dramatically illustrated by comparing photographs 29 and 30. Photograph 30 should be about 2/3 the size of 29 if the pressure decrease with distance were the only parameter involved, but instead, it is 2 times the peak value. Apparently detonation was speeded up by the pressure; however, while the peak output increases, the total energy does not change necessarily. Photograph 34 shows how the energy was more predominately spread over the lower frequency range.

Photographs 35 through 39, plate 8, are for the depths of 25, 100, 200 and 375 feet, respectively. These tests were made on another day with slightly different sea conditions, and a considerably richer
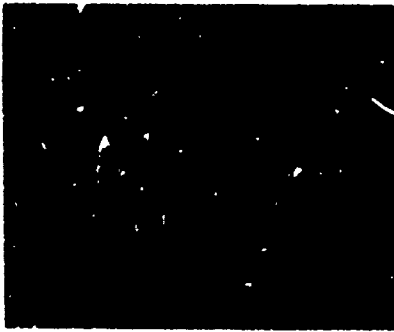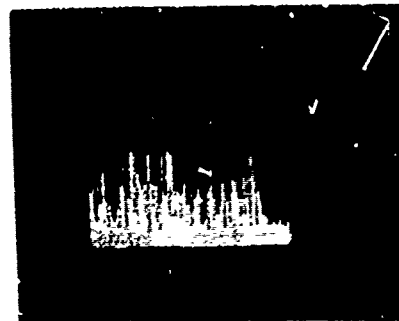
(29) 20 ms/div

(30) 20 ms/div

(31) 20 ms/div

(32) 20 ms/div

(33) 5 ms/div

(34) 0 to 600 cps
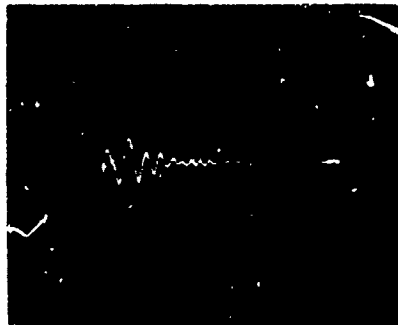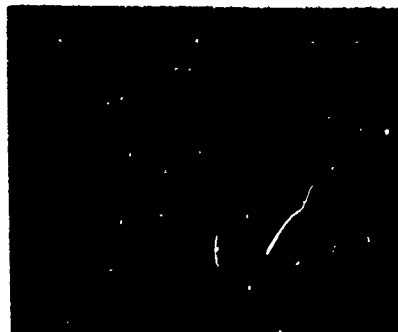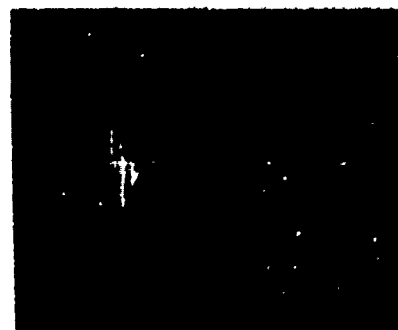
PLATE 7

20-a

(35) 20 ms/div

(36) 20 ms/div

(37) 20 ms/div

(38) 20 ms/div
PLATE 8

hydrogen mixture than those of plate 5. The increase in peak output is more pronounced and the evidence of a predominant bubble vibration frequency is apparent at 100 feet (photograph 36). Again, the effects of electrolysis under high pressure was a variable confusing the exact analysis of this set of runs, but qualitatively, the same trend shown in plate 5 is present.

The energy output for these deep transducer explosions was enough to allow echo ranging off the bottom and the surrounding underwater shelves. Photograph 13, plate 4, is an excellent example of such a multiple reflection.

The depth tests showed that it is possible to explode the gaseous mixture at depth with an increase in peak power output and a shortening of the pulse length. Due either to the change in the mechanism of electrolysis, or perhaps to pressure effects, or both, there was a drastic change in the time domain picture of the pulse. A test which could have been used to solve this ambiguity would have been to perform the electrolysis of the sea water at the surface, then explode the mixture after the transducer had been lowered to the desired depth. Unfortunately, lack of sufficient time prevented this from being done before this paper was written.

Unusual Effects: While doing the aforementioned tests, several other interesting effects were observed.

In order to see if at a depth of 100 feet a large bubble vibration was possible, a 30 minute 26 ampere charge was exploded. A large magnitude explosion resulted along with the formation of a bubble oscillation of about 70 cps. Plate 9, photograph 39, shows the results.

21
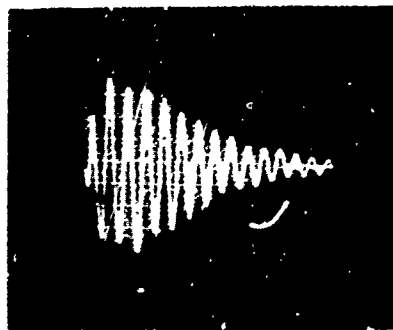
(39)   20 ms/div

(42)   20 ms/div

(40)   100 ms/div
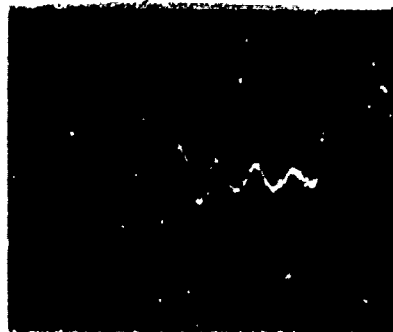
(43)   20 ms/div

(41)   100 ms/div

(44)   20 ms/div
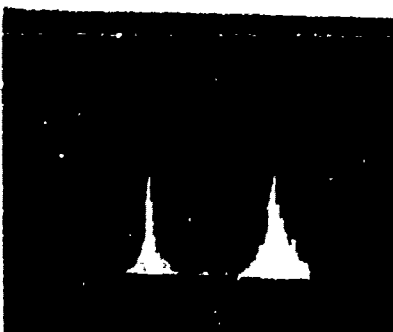
(45)   10 cps/div

PLATE 9

A calculation was made of the peak power of this explosion and it showed that about 1000 watts of peak power existed. The explosion lasted about 200 milliseconds and the total energy represented was within one order of magnitude of the theoretical energy possible.

Another interesting run is shown by photograph 40. Here, 430 milliseconds after the main explosion, another large pulse is shown. This second signal is either a reflection off the bottom (1100 feet of water) or is a second explosion in the transducer. Although this particular run could have been caused by a bottom echo, other shots were made with the same sort of results which could not be explained on the basis of reflections. Photograph 41 is one such explosion. In all cases, the double pulse runs were made with extremely rich hydrogen mixtures. It is believed that the presence of two slow-burning flame fronts or a delayed action in the chamber could cause such a secondary explosion.

A good example showing how the frequency of bubble oscillation can be controlled by mixture and depth is demonstrated in photographs 42 and 43. Here, the time domain of two different explosions are shown, similar in form but varying in frequency of oscillation. Photograph 42 has a 60 cps. fundamental frequency, while 43 has a 35 cps. fundamental frequency.

Finally, a frequency analysis of another hydrogen rich explosion is shown by photograph 45. This photograph shows both the I.F. response of the analyzer (the first hump) and the frequency of the explosion -- about 60 cps. -- the second hump. It can be seen by considering the I.F. response, that almost all the energy of the

22

explosion is contained within 5 cycles of 60 cps. Appendix G,

concerning the analyzer, discusses this calibration check more com-

pletely. Photograph 44, plate 9, is the time domain for the explosion

shown in photograph 45.

4. Conclusions and Recommendations

Based upon the measurements performed, the following conclusions were drawn:

a. It is possible by means of electrolysis to decompose sea water into an explosive gas mixture not requiring chemical additives. This method allows the satisfactory operation of a transducer of nearly unlimited depth and power capabilities. The power capability is inherent in that the device is a storage unit where, if sufficient current and/or time is available, many kilowatts of peak power are possible.

b. By changing the H_2/O_2 ratio, the explosion can be varied from a sharp pulse of broad frequency content to a long pulse exhibiting nearly single frequency output. Pulse lengths of 20 to over 500 milliseconds were obtained.

c. By changing the depth, the resonance frequency of the bubble can be changed along with the pulse shape itself.

d. By changing the input energy, the output energy and bubble frequency can be controlled.

Even with the experimental low power transducer, substantial ranges by echo ranging were recorded with a very insensitive receiver. Therefore, it is believed that the device offers considerable possibilities in the area of echo ranging as well as signalling and geophysical exploration. Of special interest is the fact that it is repetitive in nature, apparently not depth limited, and is constructionally very simple and rugged. The power requirement is a desirable factor in view of the availability of such from ships and aircraft.

The success experienced in this field of work prompts the authors

24

to make the following recommendations·

a.   The work in electrolysis of sea water (Appendix A) should
be continued especially in the area of gas production under high
ambient water pressures.

b.   An investigation of shaped transducers should be conducted
since a resonance effect could augment the production of a single
frequency or greater peak power outputs, and perhaps produce some
direc.ivity.

c.   The use of air and hydrogen as the explosive mixture should
be examined. Here, the abundance of oxygen along with a large quantity
of nitrogen creates a large bubble resonator and should allow large
output of nearly discrete frequencies.

d.   The development of a more powerful unit to operationally
check its feasibility in the areas of use mentioned   This would be
augmented by the use of a tuned receiver to enhance the S/N ratio.

e.   The deep water experiments should be conducted again under
conditions of no interference by surface or bottom reflection   The
use of deep water hydrophones would allow this to be done.

f.   The refinement of the frequency analyzer discussed in
Appendix G is recommended to allow a more qualitative investigation
of the frequency domain.

g.   The experiments should be run, using more than one hydrophone
for listening to allow greater information on the effects of depth,
attenuation, directivity, etc. for each individual explosion.

At the time of this writing, further work is being done in this
field at the U. S. Naval Postgraduate School by the authors. In

25

particular areas mentioned in d, e, f and g are being investigated.

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APPENDIX A

ELECTROLYSIS OF SEA WATER

To determine the gaseous products of sea water under different current densities and temperatures, a series of electrolysis experiments were performed. The experimental equipment consisted of the standard electrolysis glassware with platinum electrodes of about ½ inch surface area, a fast acting thermometer, a source of controllable DC current, and deaerated sea water. The latter item was considered necessary in order to obtain results consistent with the condition of the water expected at operating depths of the transducer.

A series of runs were made at currents of ¼, ½, 1, 1½ and 2 amps with the water temperature at the start about $25^{\circ}C$. A second set of runs were made at the same current settings, but with the water temperature about $80^{\circ}C$ at the beginning of the runs. Voltage varied from 10 to 100 volts, dependent on the temperature and current.

The results of the experiment showed that the negative platinum electrode gave off hydrogen only and in quantities essentially independent of the water temperature and linearly dependent upon current and time. The gas products from the positive electrode were more complex in nature. The production from this electrode was not linear with current and very dependent on water temperature. Reference 1, 2 and 3 of the bibliography, which pertain to electrolysis, indicate that complex results could be expected due to the evolution of chlorine and oxygen and other ions from both primary and secondary reactions. By use of odor and color indications, it was concluded that for low temperatures and current densities mainly oxygen was released, but

27

at higher temperatures and current densities, chlorine gas was released in increasingly larger quantities. Realizing that chlorine is considerably more soluble than oxygen, its release at the higher temperatures is to be expected.
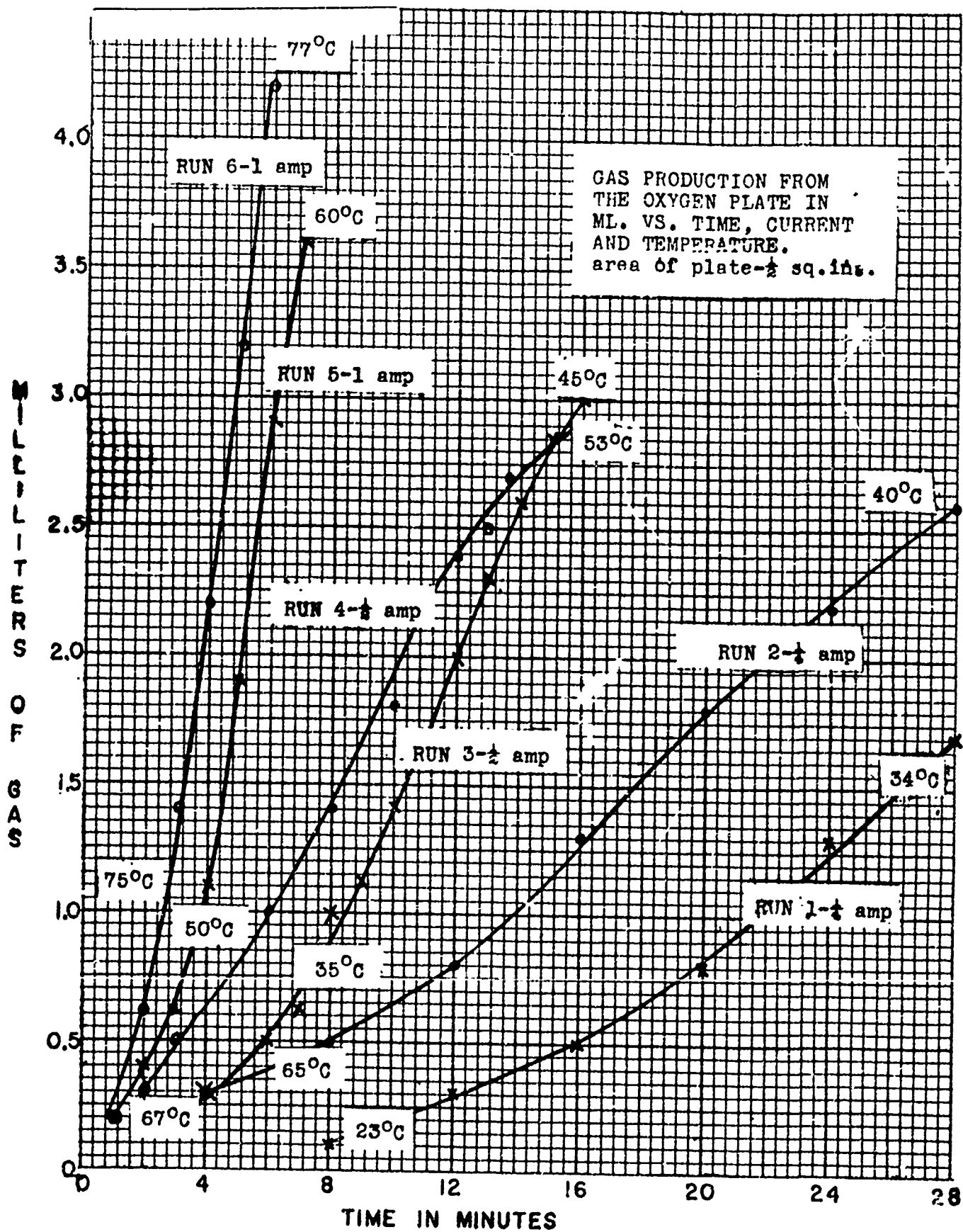
The graph (plate 10) following this appendix shows the quantity of gas released vs. time for currents of $\frac{1}{4}$, $\frac{1}{2}$ and 1 amp, under conditions of different starting temperatures. The temperature at the end of the run is also indicated. Apparently in all the runs, a certain saturation of the solution occurred for the oxygen. This is indicated on the graph by the curvature at about $\frac{1}{2}$ milliliter for nearly all the runs, representing 1/130 of the total volume of the container, and is independent of the current. Also quite evident was the dependency of the gas quantity on temperature, but even more so on current density.

A comparison of the slopes of the curves, after the apparent saturation takes place at around .5 ml. indicates a 17 to 1 hydrogen to oxygen ratio at the $\frac{1}{4}$ and $\frac{1}{2}$ amperes charging ratios and low temperatures, with a lowering of the ratio as the temperatures and current densities were increased. Comparing run 4 and run 5, operation in the same temperature region only at different current densities, shows a nearly square law current dependency, differing from the linear ratios existing at the lower current densities and temperatures.

It was concluded that at current densities of $\frac{1}{2}$ to 1 ampere per square inch and temperatures below $60^{\circ}C$, mainly oxygen alone would be released from the positive place in ratios of 17 to 1 relative to the hydrogen production. This ratio is reached only after an apparent saturation of the solution occurs. This was the environment in which

the transducer was made to operate. By proper adjustment of the trans-
ducer hydrogen plate, this ratio can be changed to the neighborhood of
2 to 1, the perfect combustion ratio for hydrogen and oxygen.

In retrospect, it was noted that higher oxygen rates could be
forced by chemically doping the water, but due to logistic replacement
problems in deep water operations and for long periods of usage, this
method was discarded for use at this time.

GAS PRODUCTION FROM THE OXYGEN PLATE IN ML. VS. TIME, CURRENT AND TEMPERATURE. area of plate—½ sq. ins.

PLATE 10
29-a

APPENDIX B

The transducer consisted of a steel cylinder 12 inches long and 8 inches in diameter with a cap welded on one end. This cylinder was lined with polyethylene to insulate the anode plate from the cathode. The polyethylene liner was actually an acid jar with the bottom removed. This provided a combustion chamber of hemispherical shape except where the neck for the cap was located. The plastic cap was used to provide for easy access to the igniter element and was tightly sealed when in place. The space between the top of the steel jacket and the polyethylene hemisphere was filled with an epoxy resin. This epoxy was also used to make a lip on the bottom of the transducer to prevent exposure of the lower edge of the steel jacket from diluting the mixture. (See enclosed drawing)

A six inch square sheet of perforated platinum was mounted inside the transducer by means of a polyethylene frame which was fastened through the polyethylene liner to the steel jacket with nylon screws. A connecting electrode was passed through a polyethylene feed-through insulator to provide electrical connection to the platinum anode.

Diametrically opposite the platinum was placed a metallic machine screw threaded through the steel jacket from the outside to provide the method for mixture control. This electrode was the only portion of the cathode exposed to the inside of the transducer and therefore produced all the hydrogen used in the combustion process. A locking nut was placed on this machine screw to firmly secure the mixture setting.

Three lifting eyes were welded to the top of the device and another one at the lower end of the steel jacket to allow the

transducer to be inverted after each explosion in order to clear the chamber of any remaining gases. In this manner each explosion was made with a completely fresh charge.

Plates 11 and 12 show details of the transducer by drawings and photographs of the completed unit.

TRANSDUCER DRAWING

lifting eye

8'

2"

polyethylene

lifting eye (3)

Ignitor wire

3/8"

3'

Cathode connector

1/4-20 x 1/2" (steel)

1 1/2"

Epoxy resin filler

steel
polyethylene

7"

1/4-20 x i" (brass)
Anode connector

Platinum sheet
(6"x6" perforated)

12"

10-32 x 3" (steel)

Mixture adjustment screw

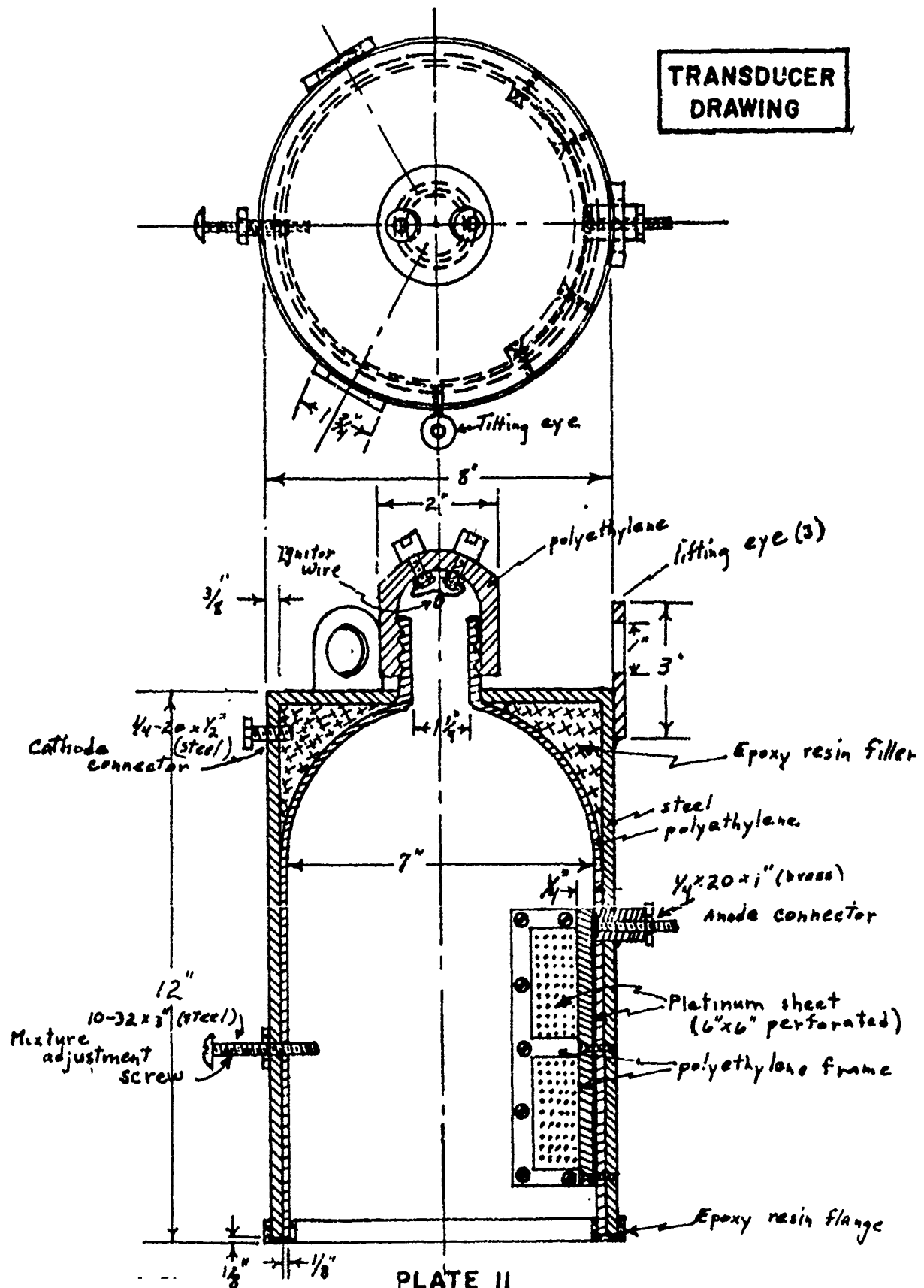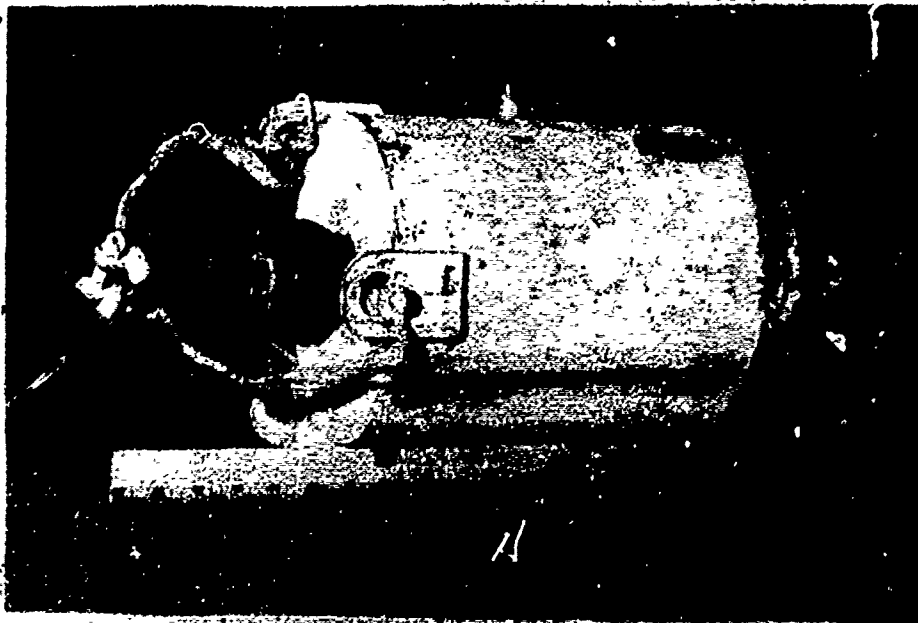polyethylene frame

Epoxy resin flange

1/8"   1/8"

PLATE II

31-a

BASIC TRANSDUCER

BASIC TRANSDUCER INTERIOR

PLATE 12

31-b

APPENDIX C

POWER CONTROL PANEL

In order to control the current to the transducer and allow a means of supplying ignitor voltage, a power control panel was constructed. In essence, meters for measuring voltage and current to the ignitor and transducer were provided along with provisions for switching in series resistances to control the current flow to either the transducer plates or the ignitor. These resistors were made out of sections of nichrome wire, capable of handling 15 amperes. To allow sufficient current capacity for the unit, parallel sets of resistors were used. The series resistance for the ignitor was adjusted for about 14 amperes, thereby insuring a red hot ignitor. On the following pages are photographs of the control panel (plate 13) and a circuit diagram (plate 14) of the same.
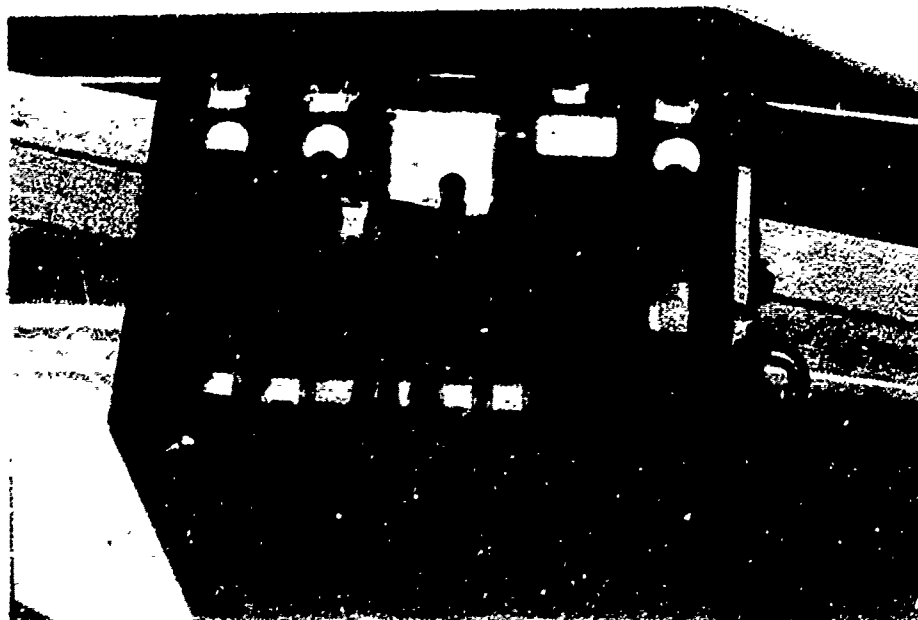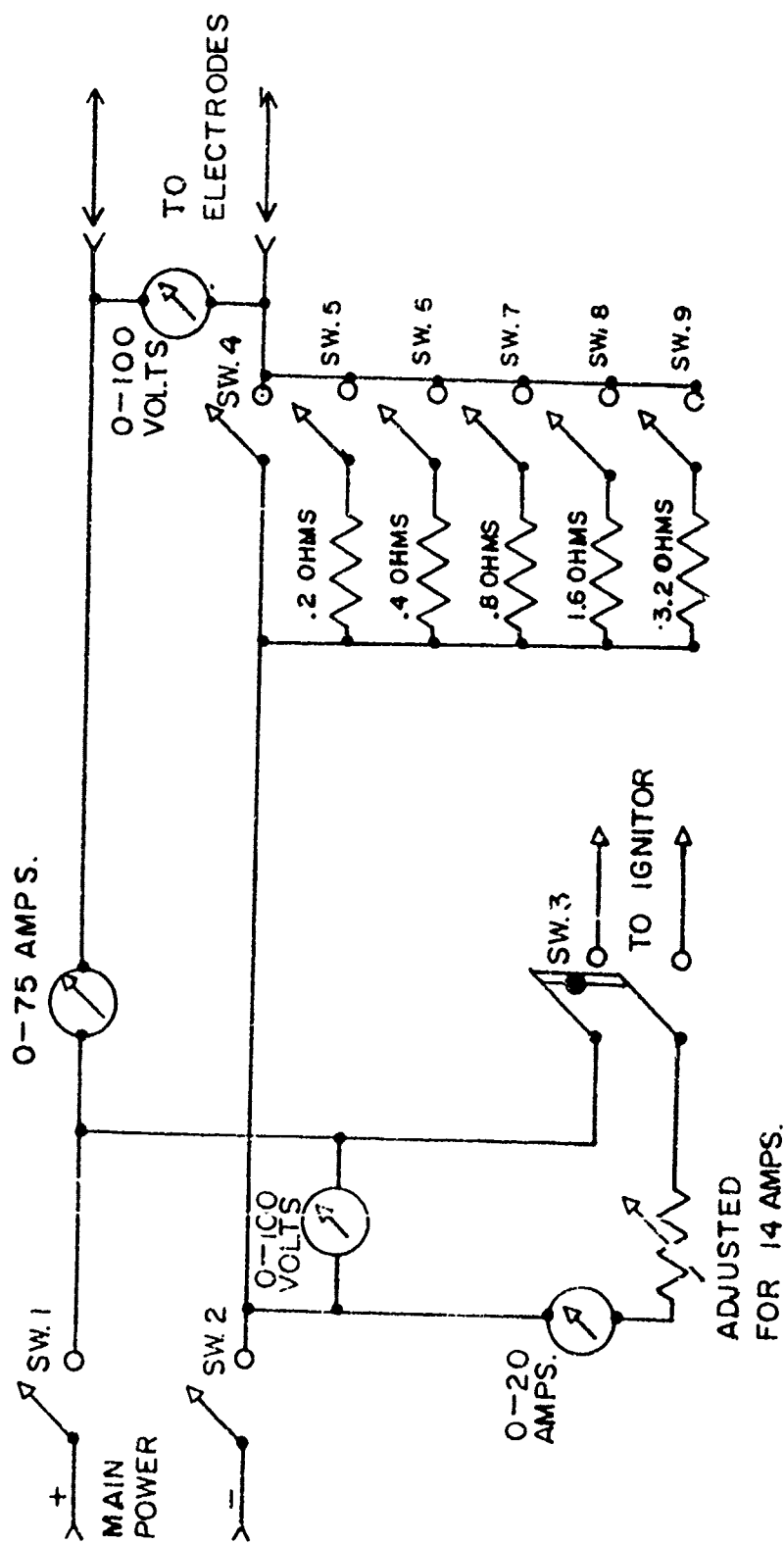
ELECTRICAL CONTROL PANEL TOP

ELECTRICAL CONTROL PANEL INTERIOR

PLATE 13

32-a

CONTROL PANEL SCHEMATIC

PLATE 14

32 - b

HYDROPHONE LINEARITY TESTS

Of primary importance in the measurements of pressure waves is the assurance that the hydrophones and preamplifiers are linear in output over the range of pressures to be measured. To insure that this was the case, a J-2 transducer, which is considered linear in operation up to 100 watts of input power at low frequencies, was placed in a tank of water and connected to a 60 watt power amplifier driven by a 55 cps sine wave. The M115-B hydrophone was suspended 3 feet away and connected to the M115 preamplifier. As the input to the power amplifier was increased, the RMS voltage across the voice coil of the J-2 transducer was recorded and plotted vs. the RMS voltage output from the M115 preamplifier. At the same time, oscilloscopes placed across both of the VTVM's were observed to insure that no distortion of the waveforms occurred.

The following graph (plate 15) is the plot of these voltages and illustrates the high degree of linearity. During actual deep water measurements, peak voltages in excess of the range of the linearity measurements were not encountered.

LINEARITY TEST
OF M115B #405
AT 55 CPS

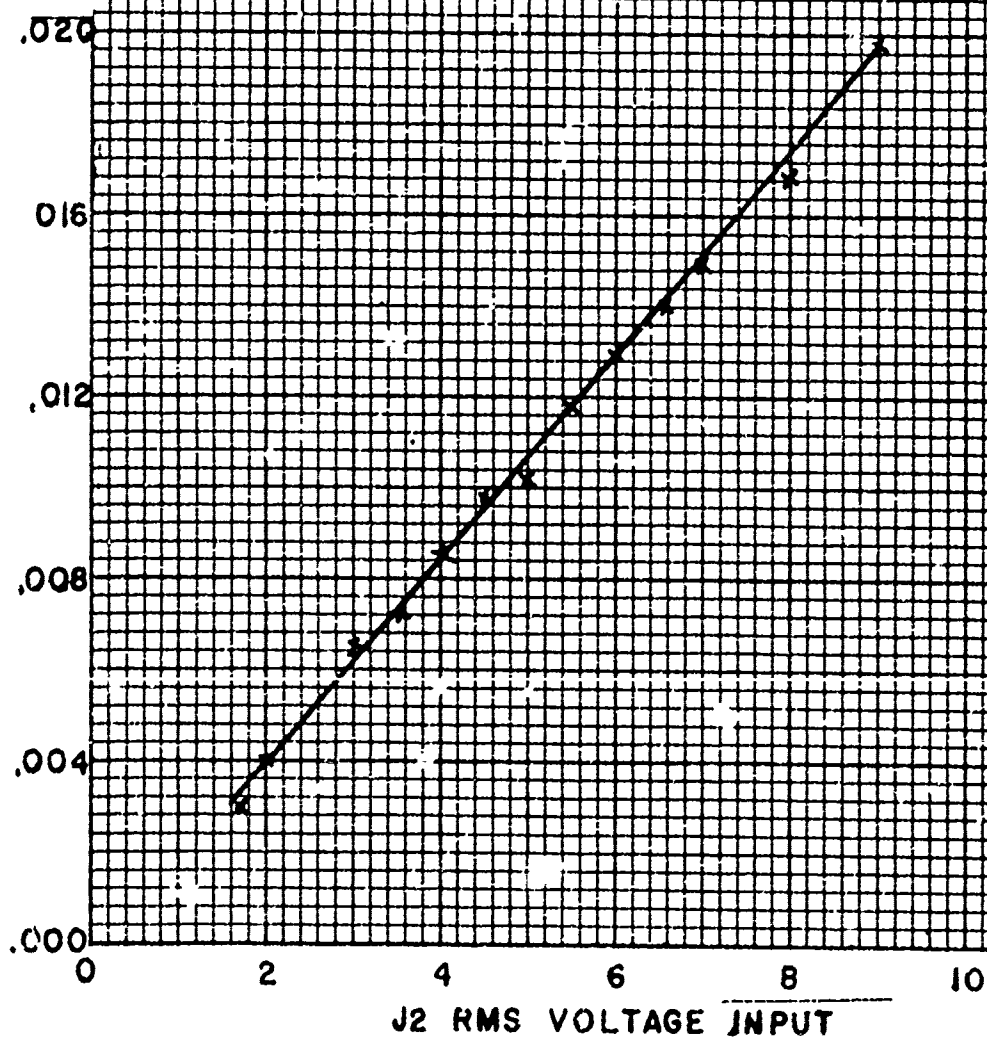M115B RMS VOLTAGE OUTPUT

J2 RMS VOLTAGE INPUT

PLATE 15

33-a

APPENDIX E

HYDROPHONE SENSITIVITY TESTS

To insure the reliability of the frequency and sensitivity

characteristics of the hydrophone used in the measurements, a calibrated

Massa Lab M115-B, serial #405, was obtained from the U. S. Naval Under-
                hydrophone

water Sound Reference Laboratory at Orlando, Florida.

It was determined after several initial explosions were analyzed

that frequencies lower than the hydrophone low frequency calibration

point (60 cps.) were encountered. It was therefore necessary to extend

the calibration curve down to 30 cycles per second. Since the original

calibration was done from 60 to 100,000 cps., and the authors' interest

was for frequency measurements in the 30 to 600 cps. range, the hydro-

phone was recalibrated from 30 to 600 cps. only. The range from 60 to

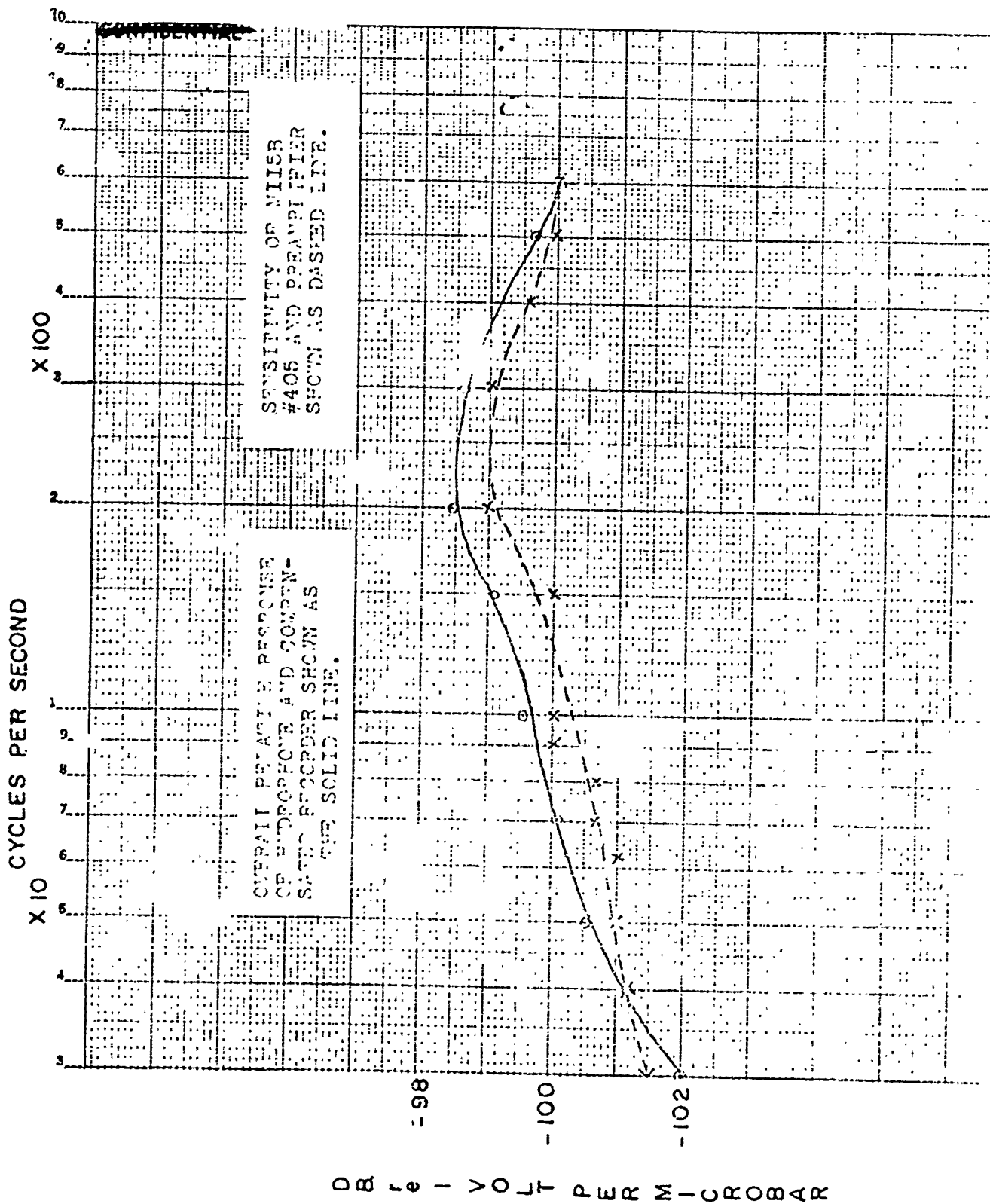600 cps. was closely checked with the original calibration curve for

correlation.

A barium titanate hydrophone of known sensitivity was obtained

from the Naval Electronics Laboratory in San Diego, California, and

used as a standard. The M115-B hydrophone and this standard were

placed in a sonar tank within 2 inches of each other and each connected

to a calibrated VTVM, the standard directly and the M115-B through its

preamplifier. The J-2 transducer (discussed in Appendix D) was placed

approximately 4 feet from the two hydrophones and excited with an

audio oscillator/amplifier combination capable of sine wave output

from 30 to 600 cps. The frequency range of interest was then scanned

and recordings taken of the output readings from the two hydrophones.

Assuming equal path lengths for the sound energy reaching the

two hydrophones from the transducer and no appreciable phase

34

difference in the two received signals good assumptions due to the low frequencies and short distances involved, it can be said that the difference in reading between the standard and the M115-B can be used to calculate the sensitivity of the M115-B. With this method, the accuracy of the readings is not affected by reflections from the tank boundaries.

Seven measuring runs were made with different orientations of the hydrophones and the J-2 transducer with less than 1½ db deviation from the mean for any of the runs.

The enclosed graph (plate 16) is the mean curve obtained, and it was found to correlate very well for 60 cps. and above with the calibration curve furnished for the M115-B by the U. S. Naval Underwater Sound Laboratory. The total relative composite frequency response of the M115-B. preamplifier (M116) and compensated Ampex 600 tape recorder is also shown on the plot (dashed line). The overall response was $\pm$ 2 db in the range from 30 to 600 cps. and was considered sufficiently flat for qualitative analysis of the acoustic behavior encountered.

X 100

X 10   CYCLES PER SECOND

SENSITIVITY OF NIISB
#405 AND PREAMPLIFIER
SHOWN AS DASHED LINE.

OVERALL RESPONSE
OF HYDROPHONE AND SOUND-N-
SATER RECORDER SHOWN AS
THE SOLID LINE.

DB re - VOLT PER M-CROBAR

-98   -100   -102

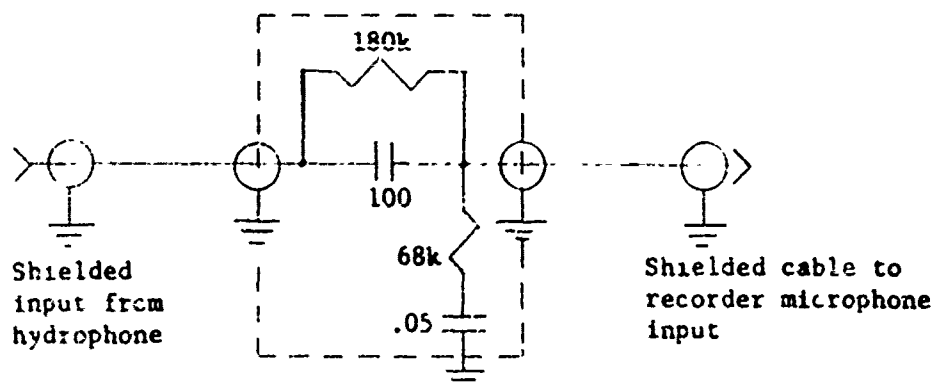PLATE 16

35-a

APPENDIX F

TAPE RECORDER COMPENSATION

In order to use the Ampex 600 tape recorder at the frequencies encountered in the explosions, it was necessary to compensate the recorder to obtain a flatter response than the 2 db points at 50 and 10,000 cps. as advertised for the recorder.

Experimentally selected values of R and C for a low and high pass filter to the microphone input of the recorder provided a considerable extension of the frequency response. In addition to compensating the response. the recorder was checked for frequency response as a function of input signal level. Plate 17 is a graph of the final frequency response (compensated) for two different input signal levels, 0 and 15 db. As indicated by the plot, the low frequency response was not affected by input level, but the high frequency response deteriorated with the use of higher input levels.

Low noise magnetic tape was used with low level signal input to insure maximum frequency response, although as it turned out later, the higher frequencies did not enter into the analysis.

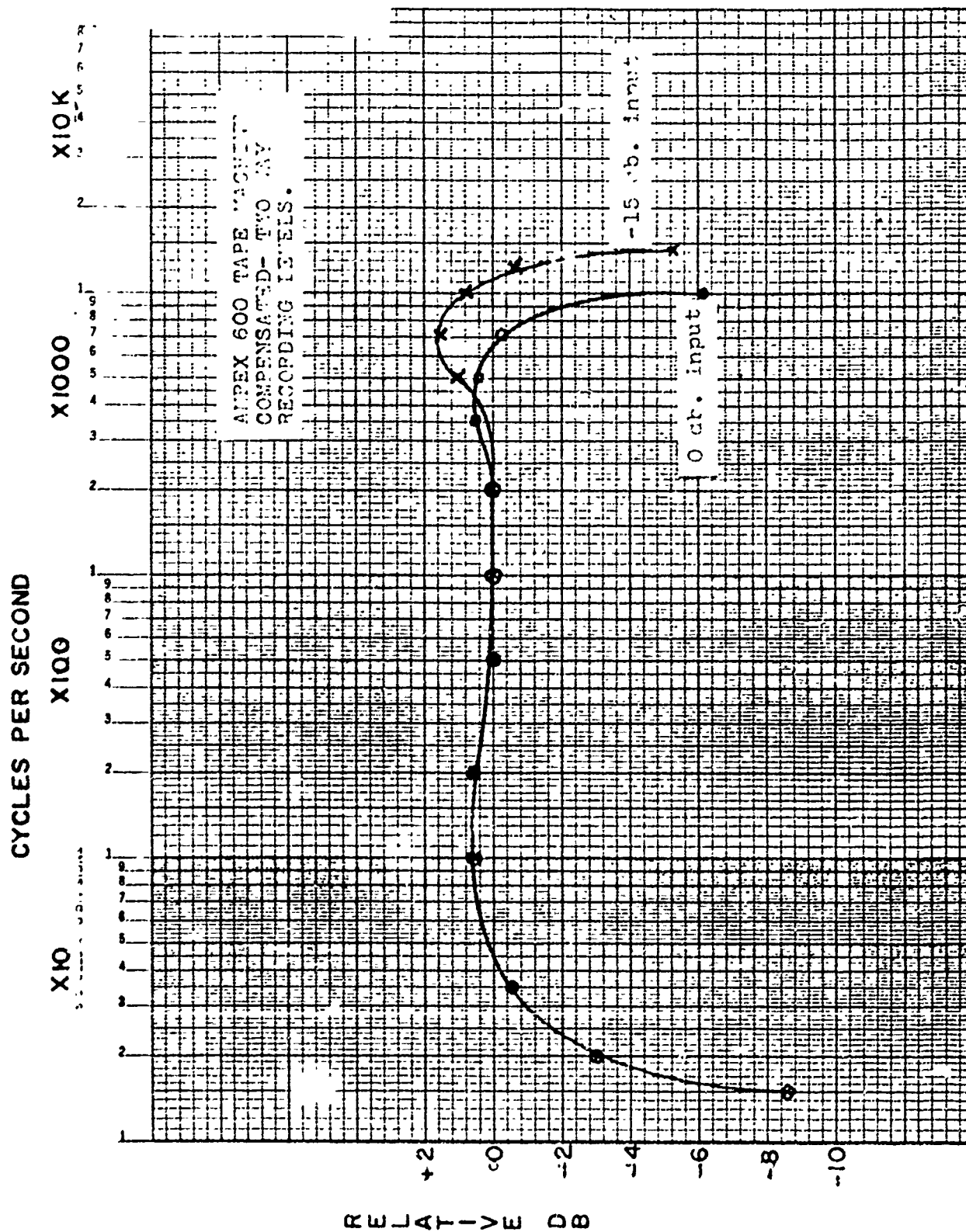The circuit of the compensation network is shown below.

CYCLES PER SECOND

AMPEX 600 TAPE MACHINE
COMPENSATED—TWO AY
RECORDING LEVELS.

−15 db. input

0 db. input

RELATIVE DB

PLATE 17

36-a

APPENDIX G

THE FREQUENCY ANALYZER

In order to allow a more complete analysis of the explosions, it was deemed necessary to investigate their frequency spectrums. Due to the short pulse width and complex nature of the explosions, the standard 1/3 octave filter techniques were not applicable. It was desirable to have a system which would produce a picture of amplitude vs. frequency for analysis similar in nature to the amplitude vs. time photographs. Equipment exists which will give this type of results but for reasons of incompatability, awkwardness in use or very high cost, they did not perfectly suit the needs of the investigators. Because of this, a system was developed which would allow taped explosions to be processed and pictorially displayed on the face of an oscilloscope. Again, the Hughes Memoscope was used, allowing simplification in analysis and photography.

Functionally speaking, each taped explosion was formed into a closed loop which, when placed on the tape machine, would allow the signal to be played back continuously at about 1½ second intervals. The output of the recorder was then fed into a specially designed sweep frequency audio superheterodyne and integrator which continuously searches different portions of the frequency spectrum, integrating the information throughout the pulse length and presenting it to the DC amplifier of the storage tube of the oscilloscope. The same mechanism which is slowly sweeping the frequency of the audio superheterodyne is also connected to the horizontal sweep oscillator of the oscilloscope, thereby giving a picture of amplitude vs. frequency.

The and a superheterodyne functionally is a receiver with untuned input to a balanced mixer, the balanced mixer being necessary if operation at low audio frequencies was to be successful. The local oscillator is influenced by the reactance tube which is driven by the voltage on the horizontal plates of the oscilloscope. The output of the mixer is fed to an I.F. amplifier tuned to 6350 kcs. This I.F. amplifier is in reality an oscillator adjusted to the verge of oscillation thereby giving a means of obtaining a high degree of selectivity. Selectivity in the order of 5 cps. bandwidth was obtained. The output of the I.F. amplifier is fed to an integrator, threshold limited to prevent the internal noise of the receiver from also being continuously integrated. The output of the integrator is connected to the DC vertical amplifiers of the oscilloscope, and also to a set of contacts on a relay which operates every revolution of the tape to clear the integrator by shorting the integrator's condenser to ground between each frequency search. The closed loop tape has a one inch aluminum foil strip fastened to it in such a position as to open the relay contacts during the period of the signal output During the remainder of the tape travel, the relay contacts are closed, thereby shorting out the integrator output. This method prevents the integrator from reading out the ambient tape noise and any extraneous water noises which are recorded during the reception of the explosion.
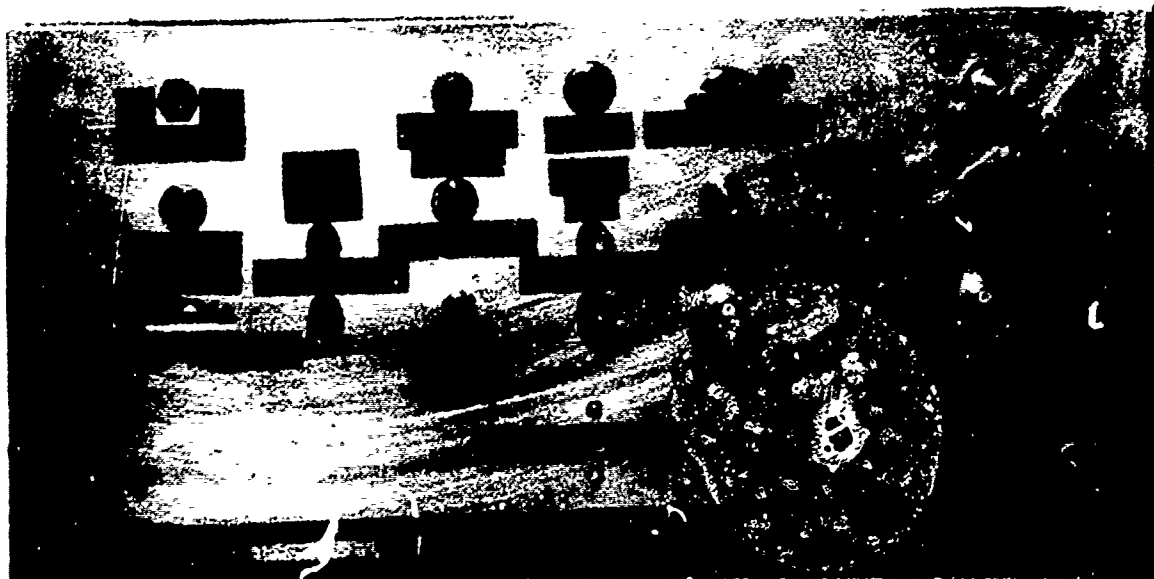
Plate 18 is a photograph of the Ampex 600 tape recorder adapted for close loop operation. Plate 19 is also a photograph showing the frequency analyzer itself, while plate 20 shows the complete setup for frequency analysis. Two regulated power supplies can be seen
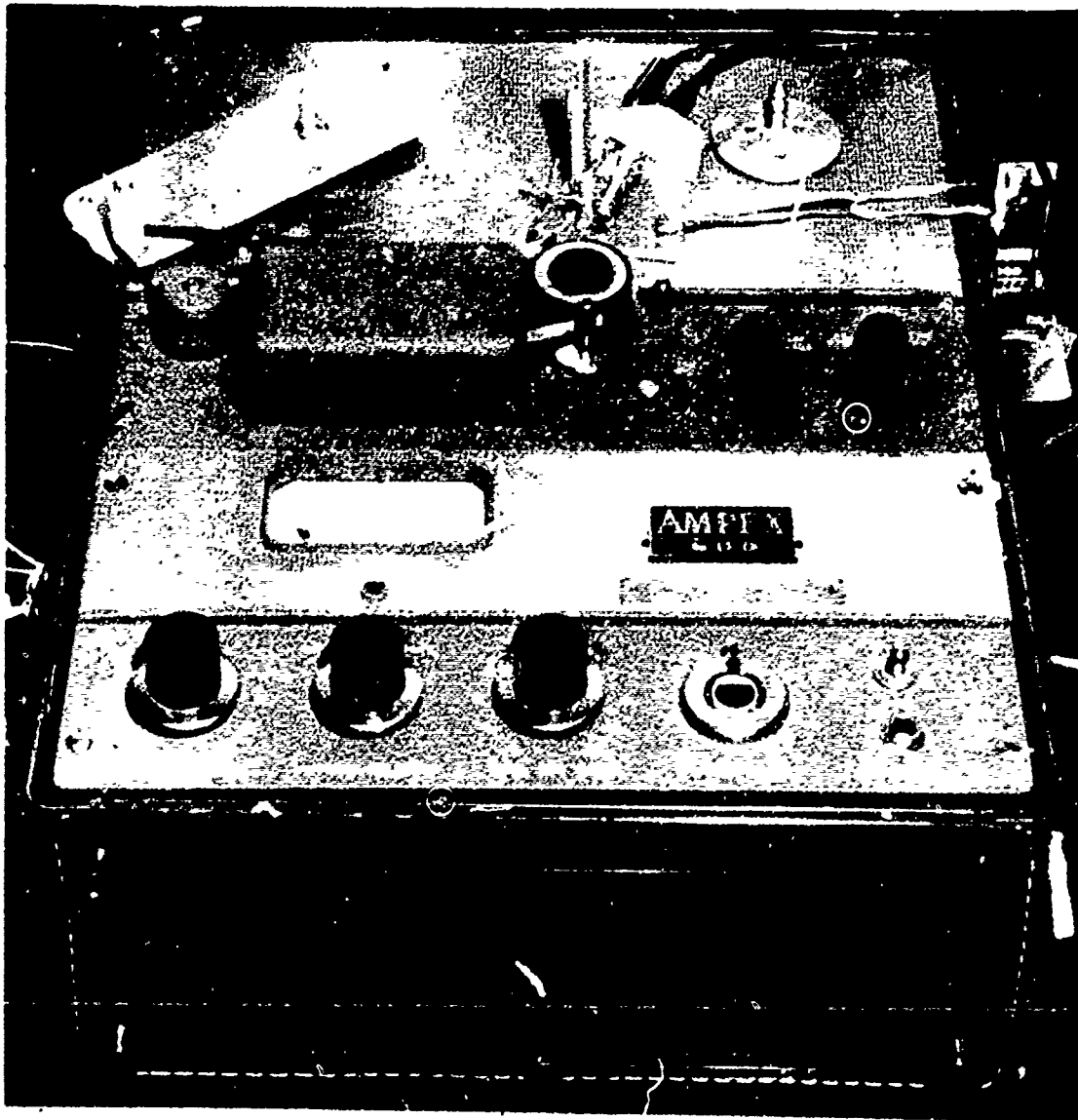
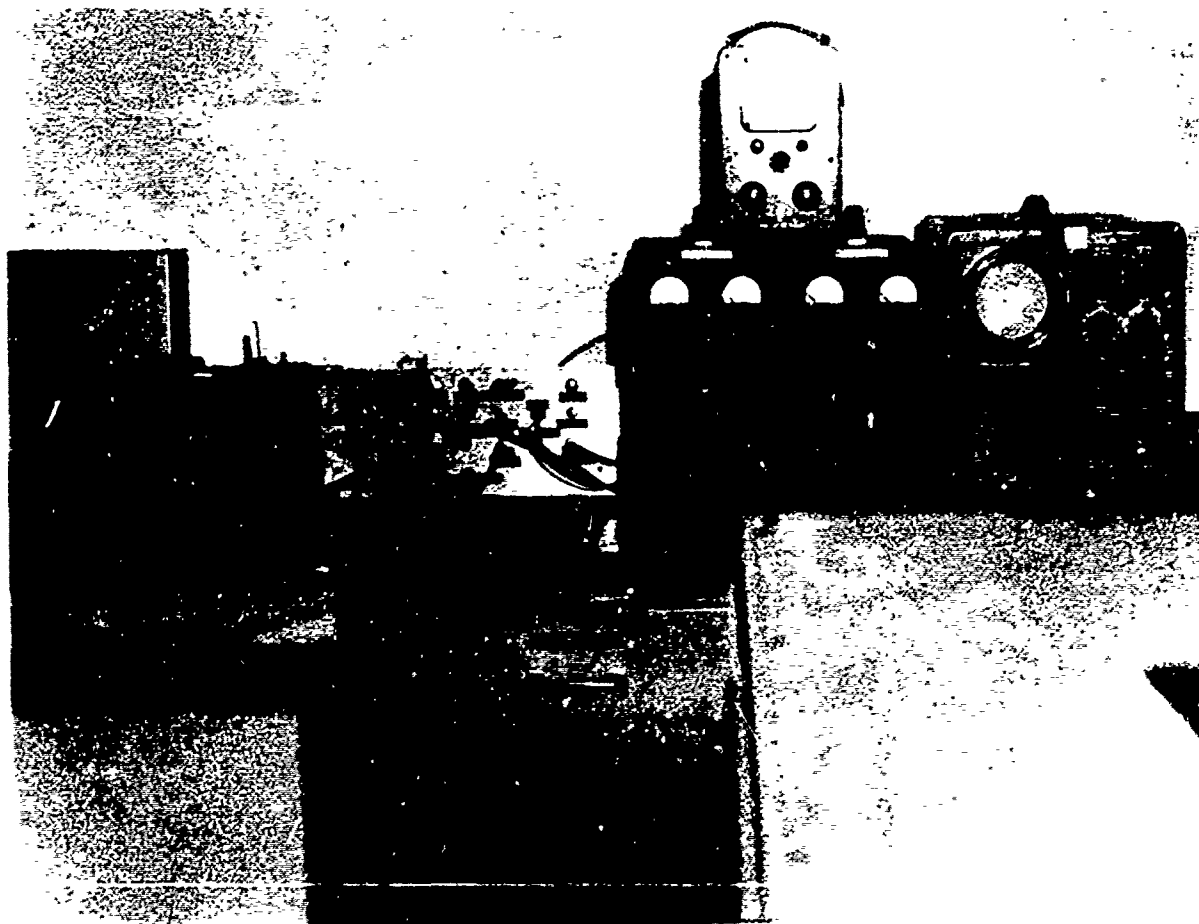TAPE RECORDER MODIFIED FOR CLOSED LOOP OPERATION

PLATE 16

32-a

FRONT PANEL OF FREQUENCY ANALYZER

PLATE 19

38-b

COMPLETE FREQUENCY ANALYZING SET-UP

PLATE 20

38-c

in the picture, and another regulating unit is built into the analyzer itself. Operation of the analyzer is very critical. The balanced modulator requires both phase and amplitude balance controls if analysis of frequency components below 100 cps. is to be done. The extra regulation on the I.F. amplifier was required to obtain a high degree of selectivity. Even with these precautions, the analyzer can only insure amplitude accuracies within a couple of db for any given input signal. This deviation can be directly attributed to the I.F. amplifier and is an area subject to further improvement. A logical solution is the use of a crystal filter nonregenerative I.F. amplifier, but time did not allow this method to be utilized during the period of the work for this thesis. As discussed in the chapter on conclusions, this aspect of improvement is being investigated.

The circuit of the analyzer is shown on plate 21. Plate 22 contains photographs of the analysis of selected explosions. To observe the I.F. spectrum of the receiver, the local oscillator was allowed to sweep through the I.F. frequency with the mixer unbalanced. Photograph a is a picture of this showing that the bandwidth was about 5 cps. To check the operation of the unit exactly, a short pulse of known values was fed to it. This signal was 2½ cycles of a 100 cps. note, whose theoretical spectrum was known by means of a Fourier analysis. Photograph b is the actual spectrum obtained from the analyzer. The width of the signal centered around 100 cps., and the minor lobe around 170 cps. is in agreement with the sin x/x distribution expected from the Fourier analysis. It also shows the anomalies in amplitude preventing precise measurements from being made.
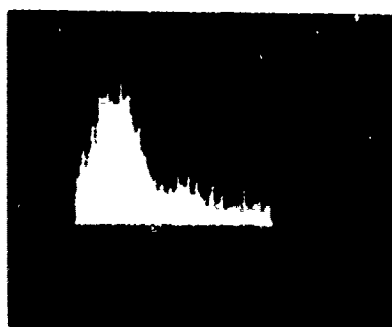
39

FREQUENCY ANALYZER SCHEMATIC
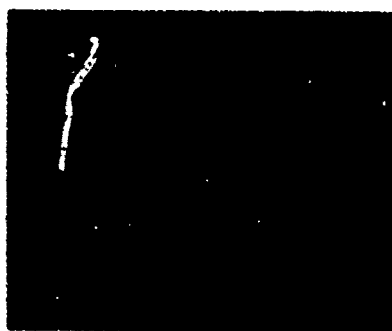
PLATE 21
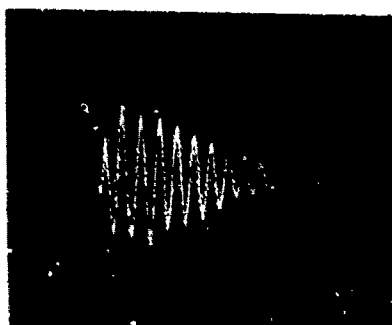
39-a
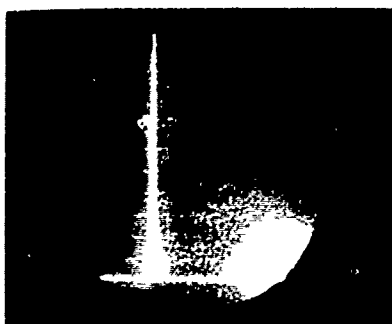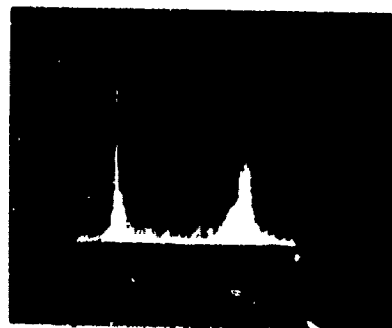
(a)   10 cps/div

(d)   0 cps   60 cps
      10 cps/div

(b)   60 cps + 260 cps
      20 cps/div

(e)   20 ms/div

(c)   20 ms/div

(f)   0 to 600 cps

PLATE 22

39-8

Photograph c is the time spectrum of one of the explosions, while d is the frequency spectrum, with the first peak representing the I.F. response and DC frequency. At 60 cps.. the explosion frequency response is shown to be wider than the I.F. response due to the finite pulse duration involved. Photograph e is another explosion time spectrum, while photograph f is of its frequency spectrum up to 600 cps. As can be seen, no appreciable energy exists except at the fundamental frequency of the long pulse bubble vibration.

A frequency sensitivity check on the analyzer showed essentially a flat response to 5000 cps. The frequency linearity was also checked and by adjusting the reactance tube bias carefully, an essentially linear frequency curve was obtained. This was enhanced by the slightly peculiar mode of operation of the reactance tube which gave a more constant local oscillator output voltage along with a more linear region of frequency vs. input voltage from the oscilloscope horizontal plates. Plate 23 is a plot of the local oscillator voltage vs. reactance tube grid voltage showing the essentially linear frequency relationship from 6850 kc to 7450 kc. representing 0-600 cps. for the analyzer.

One calibration procedure done on the analyzer was to plot the input signal to the analyzer with respect to output voltage of the integrator. This allowed a check of the sensitivity linearity of the unit and the deviation of gain of the set for several constant input signals. Plate 24 is this graph, showing the gain characteristics of the unit for the magnitude of input voltage used, along with the deviation of gain that existed over a short period of time (5 minutes).

GRAPH OF LOCAL OSCILLATOR
FREQUENCY VS. REACTANCE
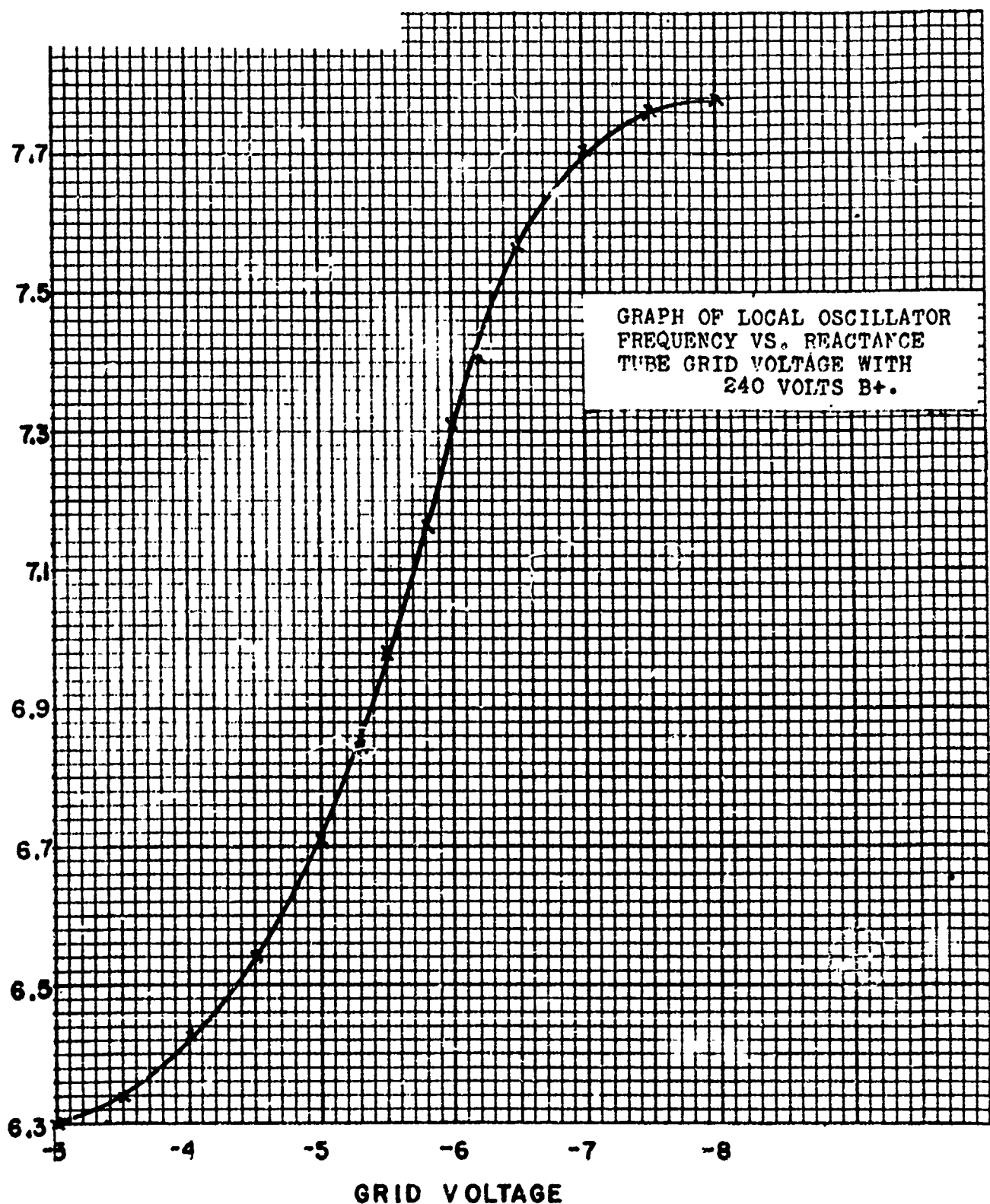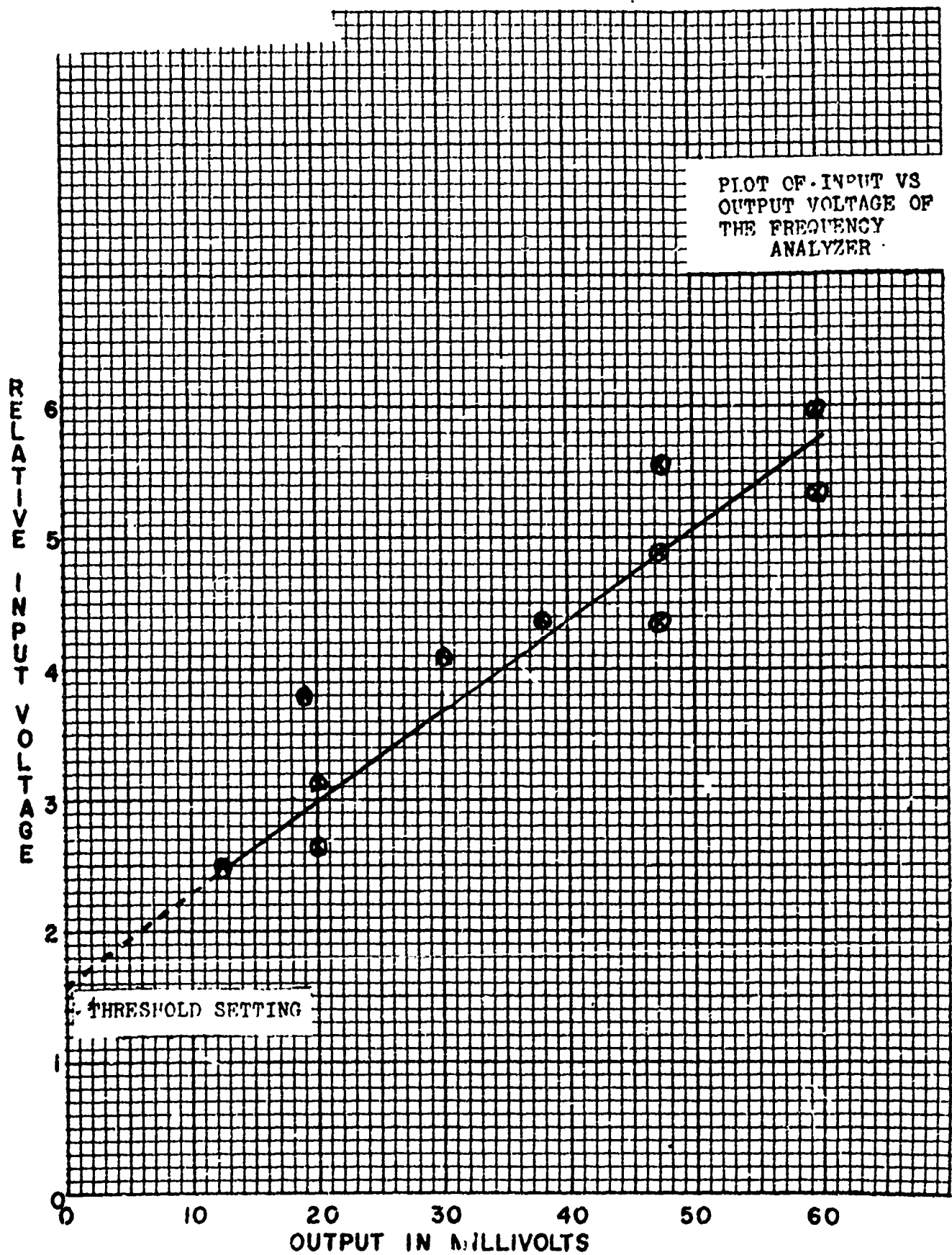TUBE GRID VOLTAGE WITH
240 VOLTS B+.

GRID VOLTAGE

LOCAL OSCILLATOR FREQUENCY IN KILOCYCLES

PLATE 23

40-a

PLOT OF INPUT VS
OUTPUT VOLTAGE OF
THE FREQUENCY
ANALYZER

THRESHOLD SETTING

RELATIVE INPUT VOLTAGE

OUTPUT IN MILLIVOLTS

PLATE 24

40-b